e4ν

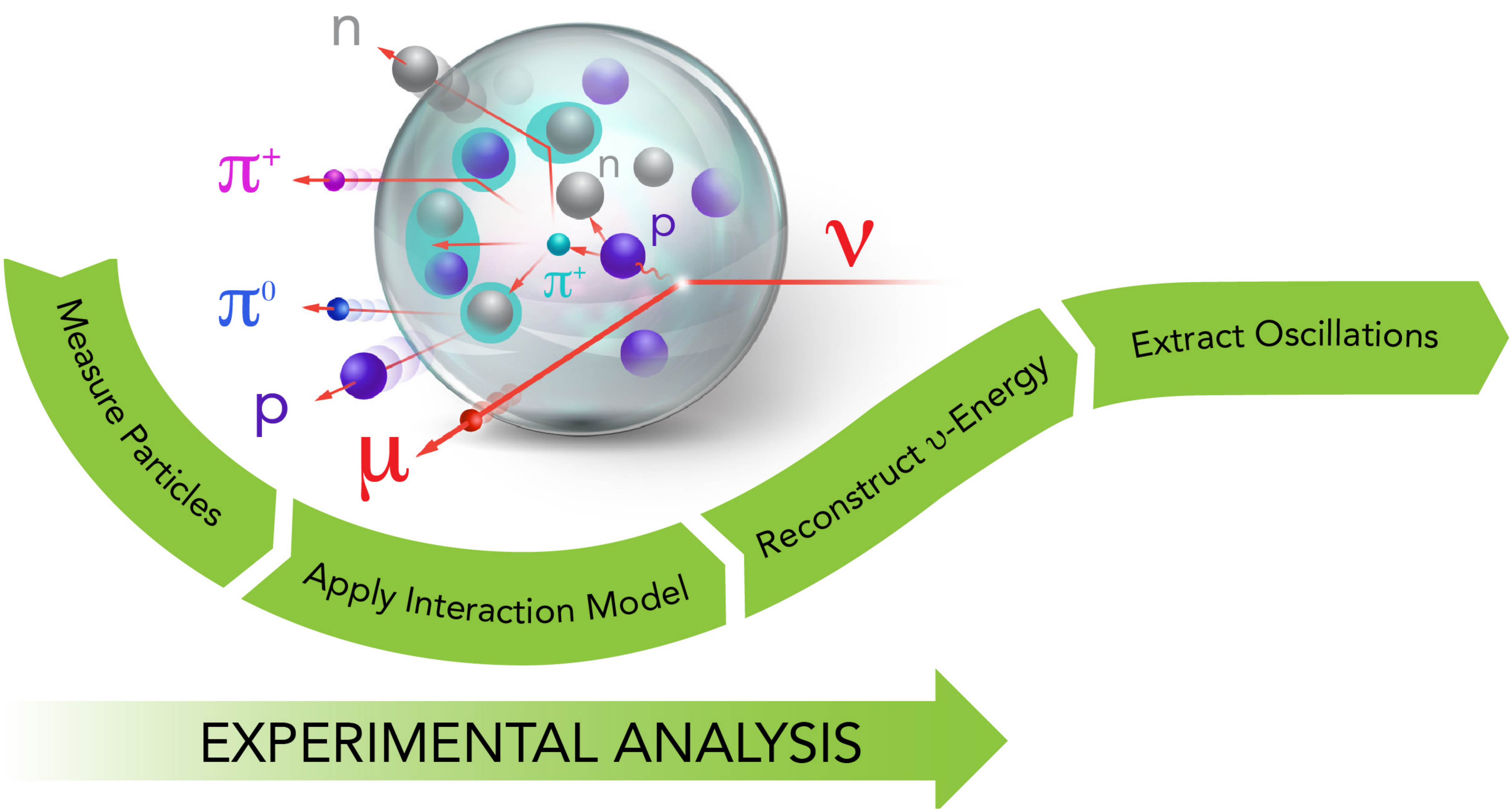
electrons for neutrinos

Fermilab Neutrino Seminar Series
05/07/2020

Adi Ashkenazi


Measure Particles
Apply Interaction Model
Reconstruct ν-Energy
Extract Oscillations


EXPERIMENTAL ANALYSIS



n
n
π+
p
π+
ν
π0
p
μ
Measure Particles
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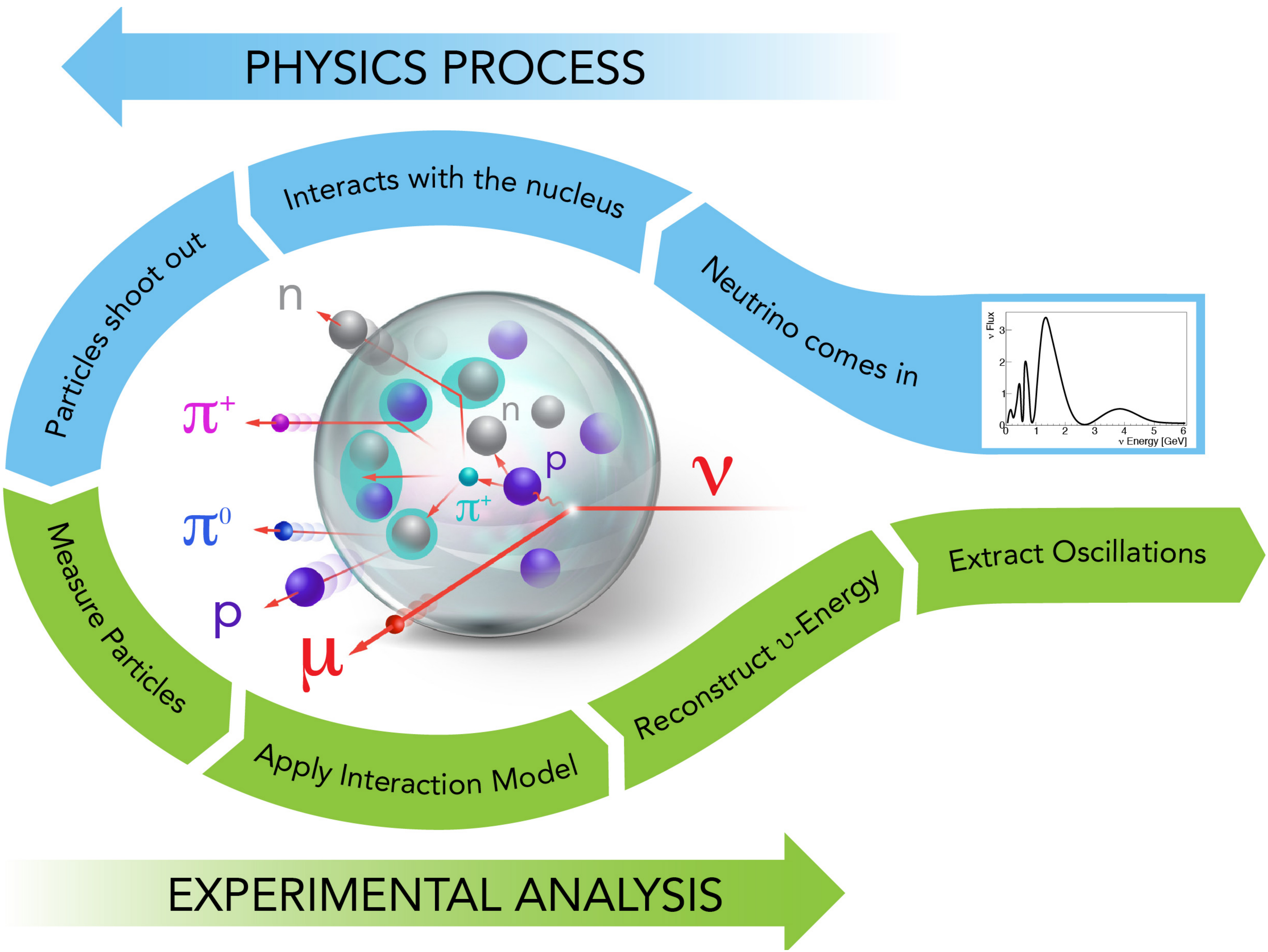
EXPERIMENTAL ANALYSIS


PHYSICS PROCESS
Interacts with the nucleus
Particles shoot out
Neutrino comes in
ν Flux
ν Energy [GeV]
n
n
p
p
π^+
π^+
π^0
ν
μ
Measure Particles
Apply Interaction Model
Reconstruct υ-Energy
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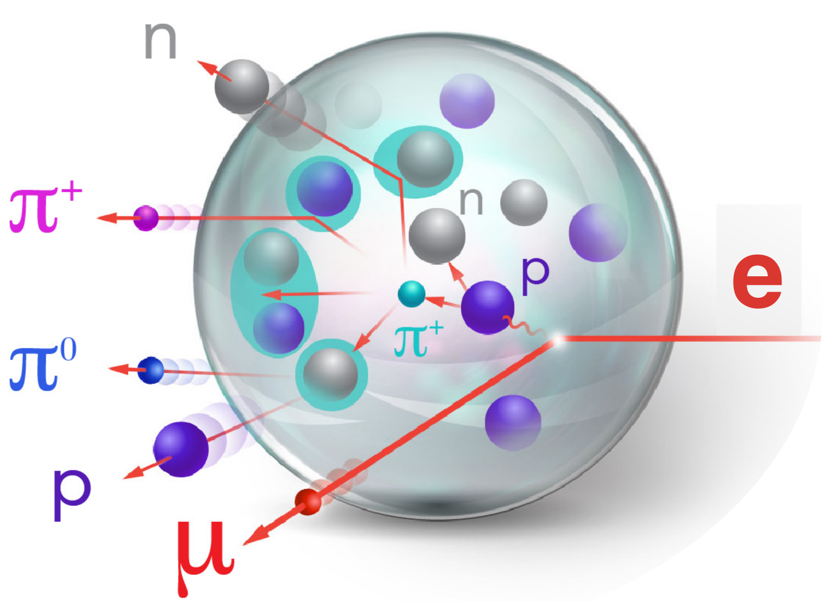
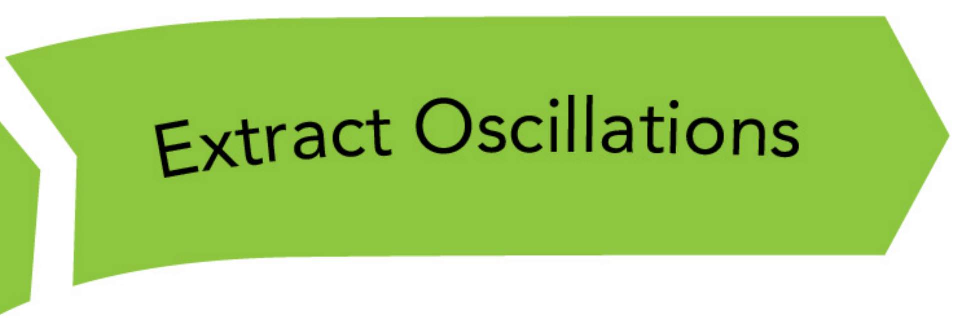
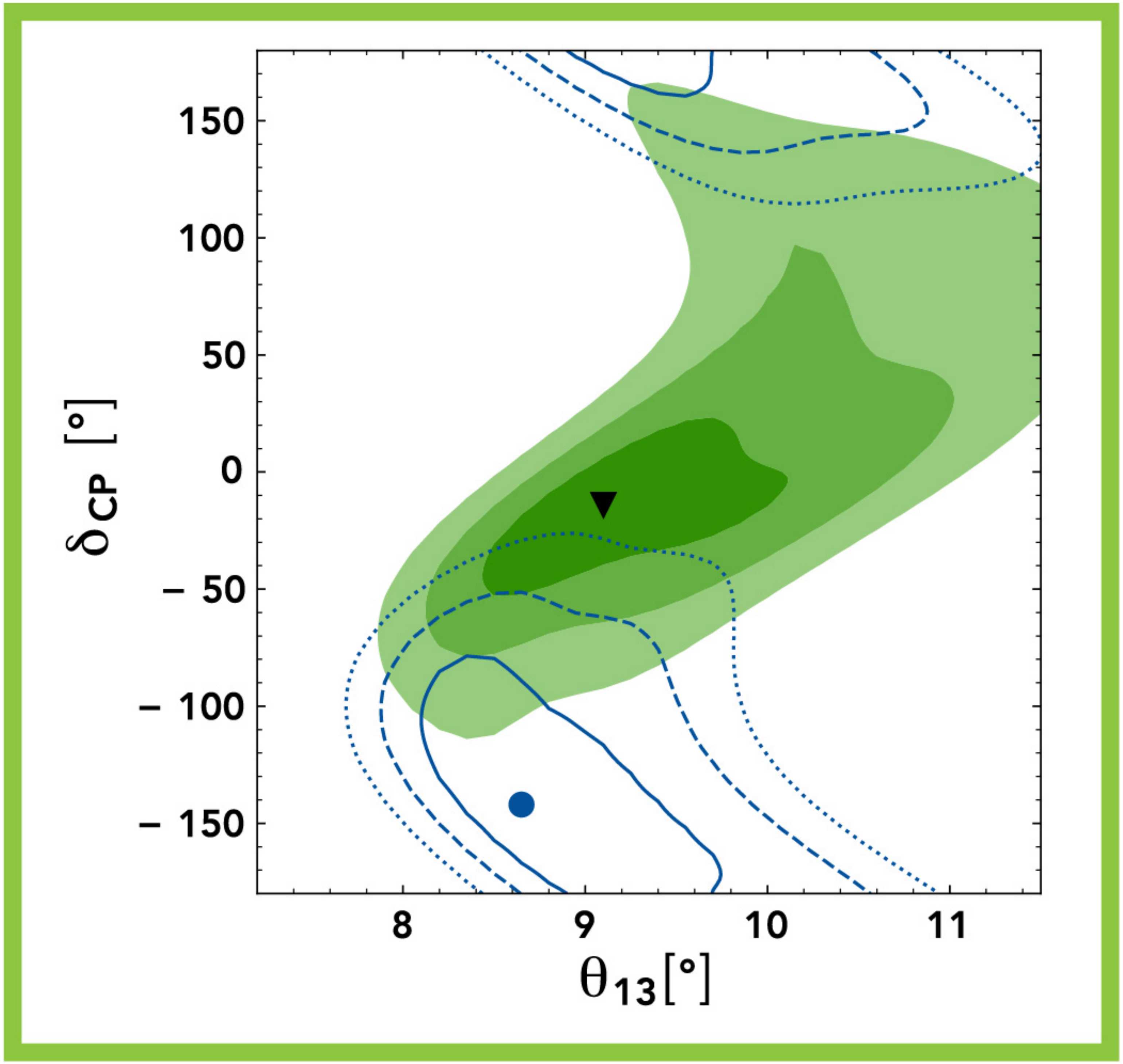
EXPERIMENTAL ANALYSIS

e4ν Electron data shows impact on extraction







Introduction to Neutrino Oscillations

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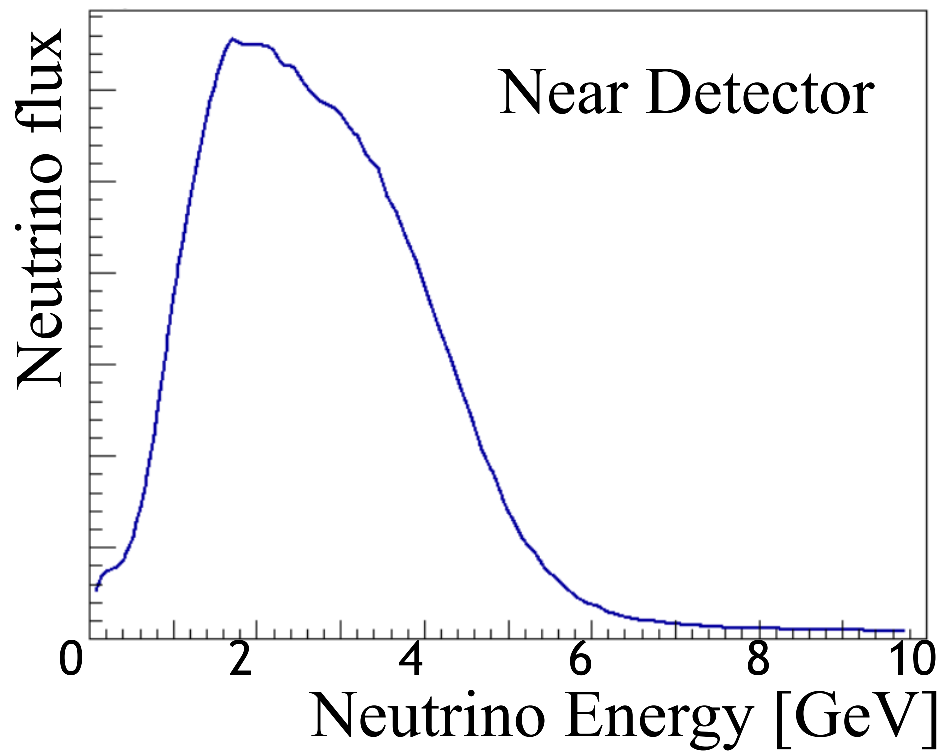
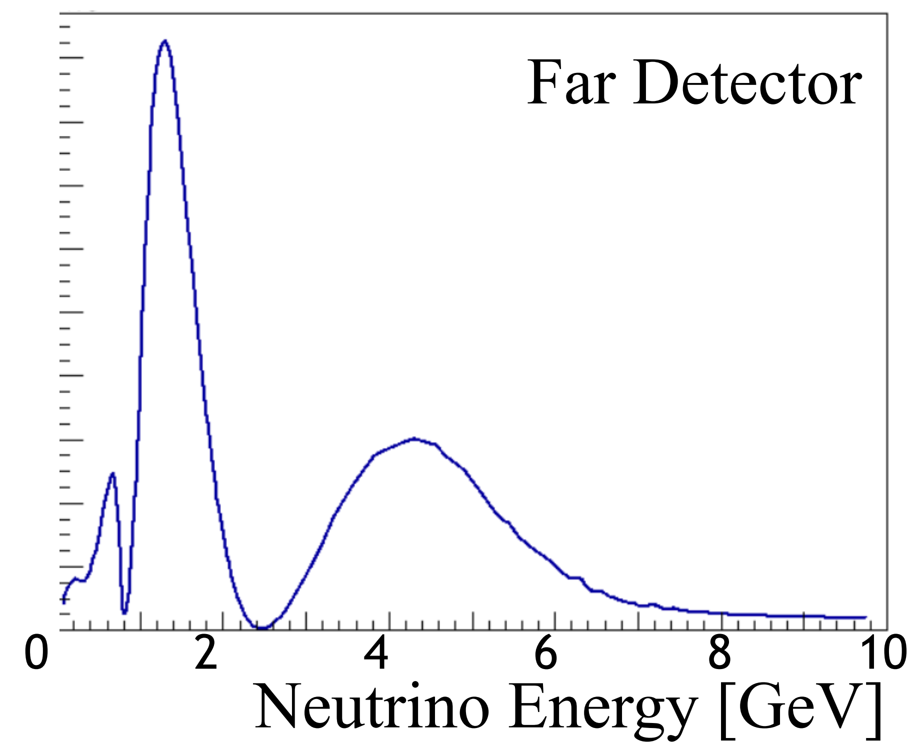
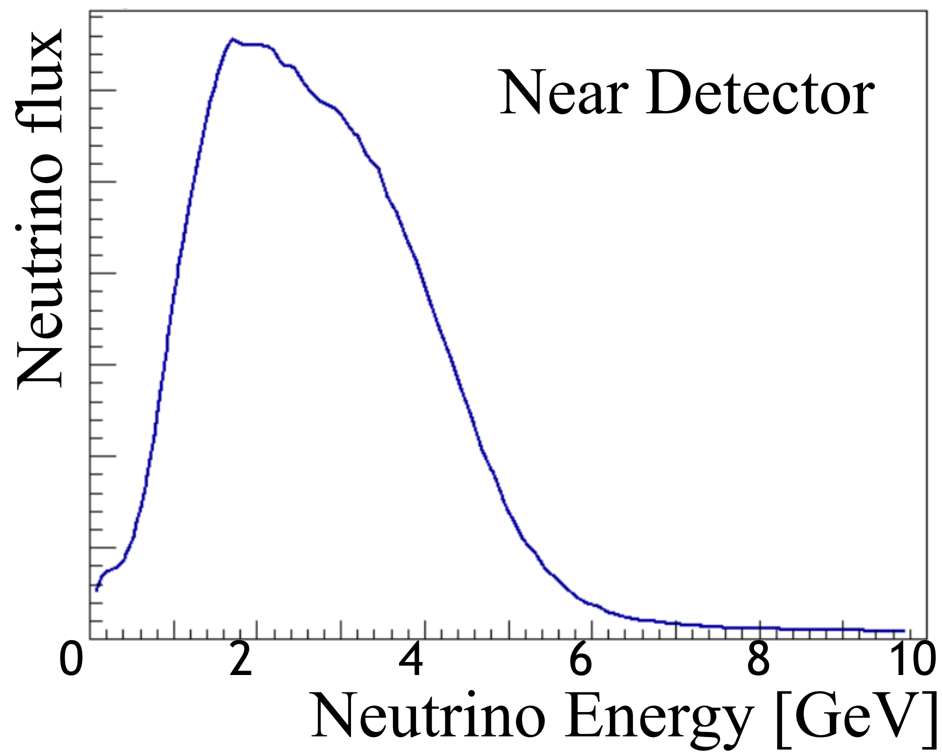
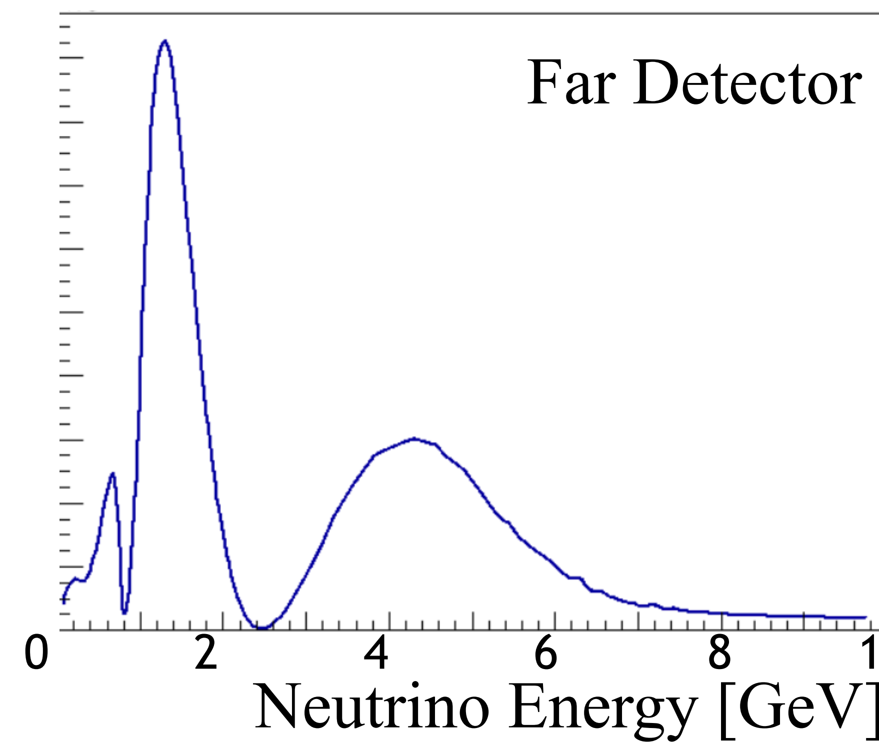




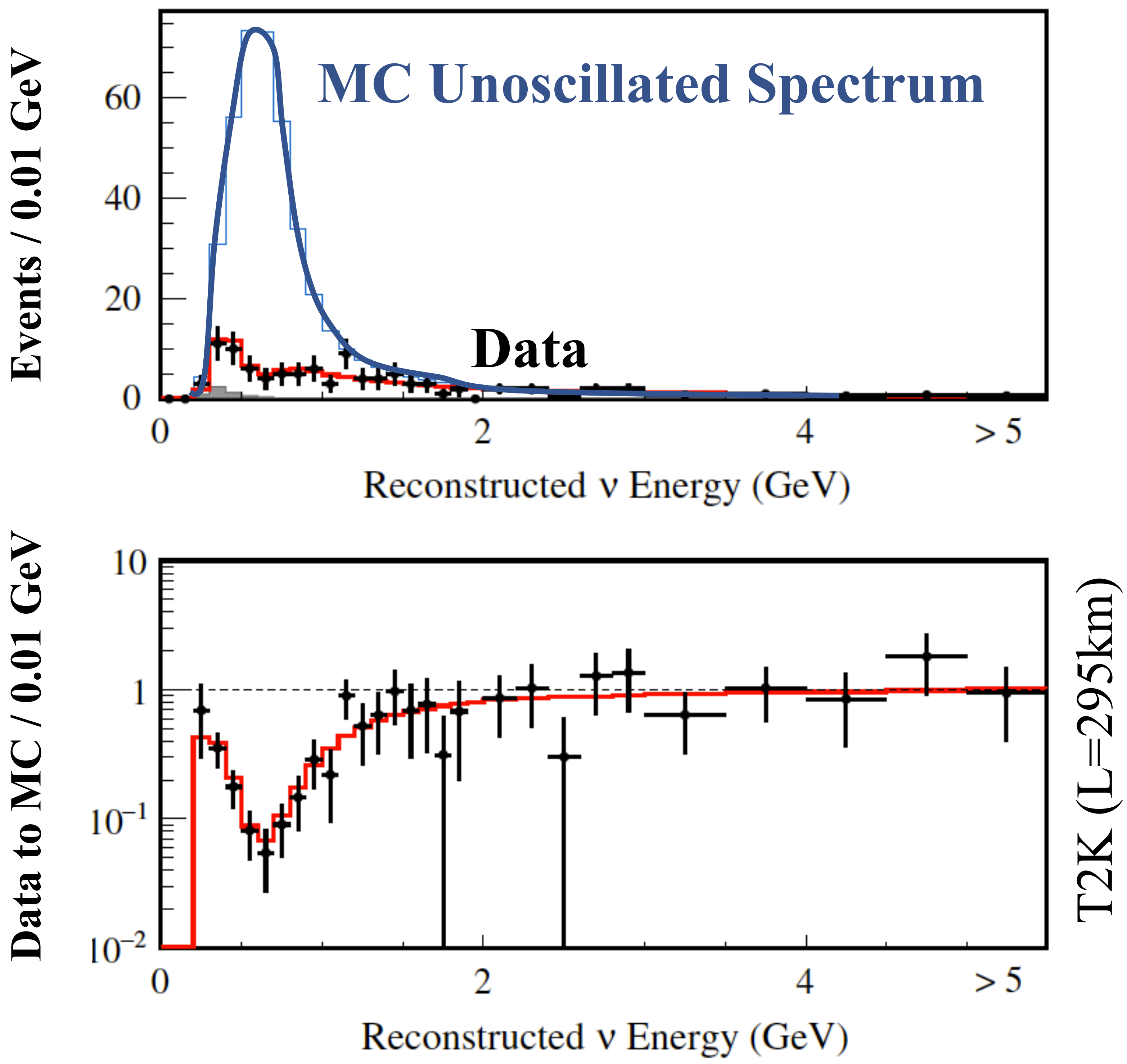
Introduction to Neutrino Oscillations

$$N(E_{rec}, L) \propto \int \Phi(E, L)\sigma(E) f_\sigma(E, E_{rec}) dE$$





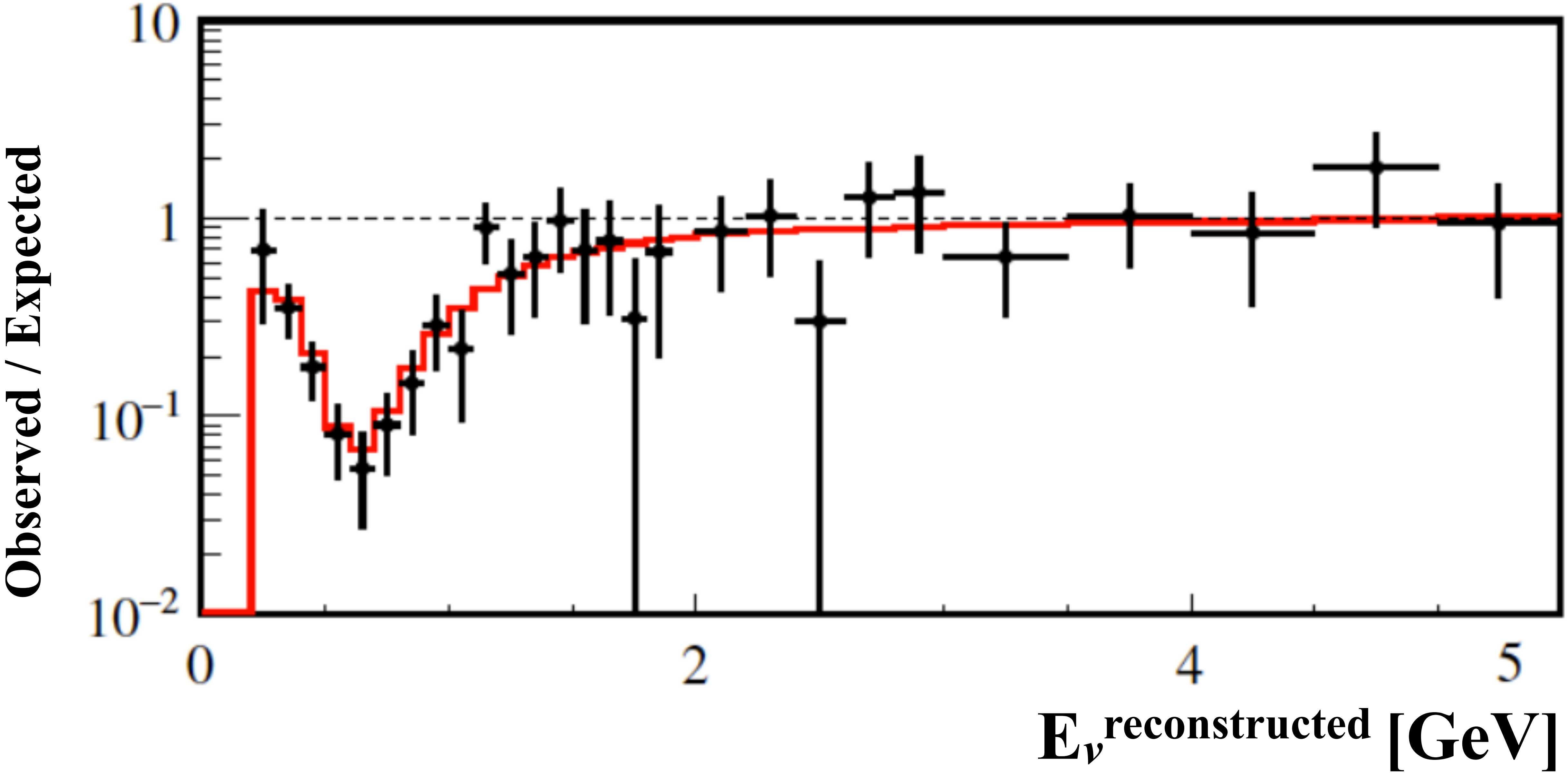
Oscillations Require E_ν Reconstruction



 T2K, Phys. Rev. D 91, 072010 (2015)

Oscillations Require E_ν Reconstruction

$$P(\nu_\mu \to \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



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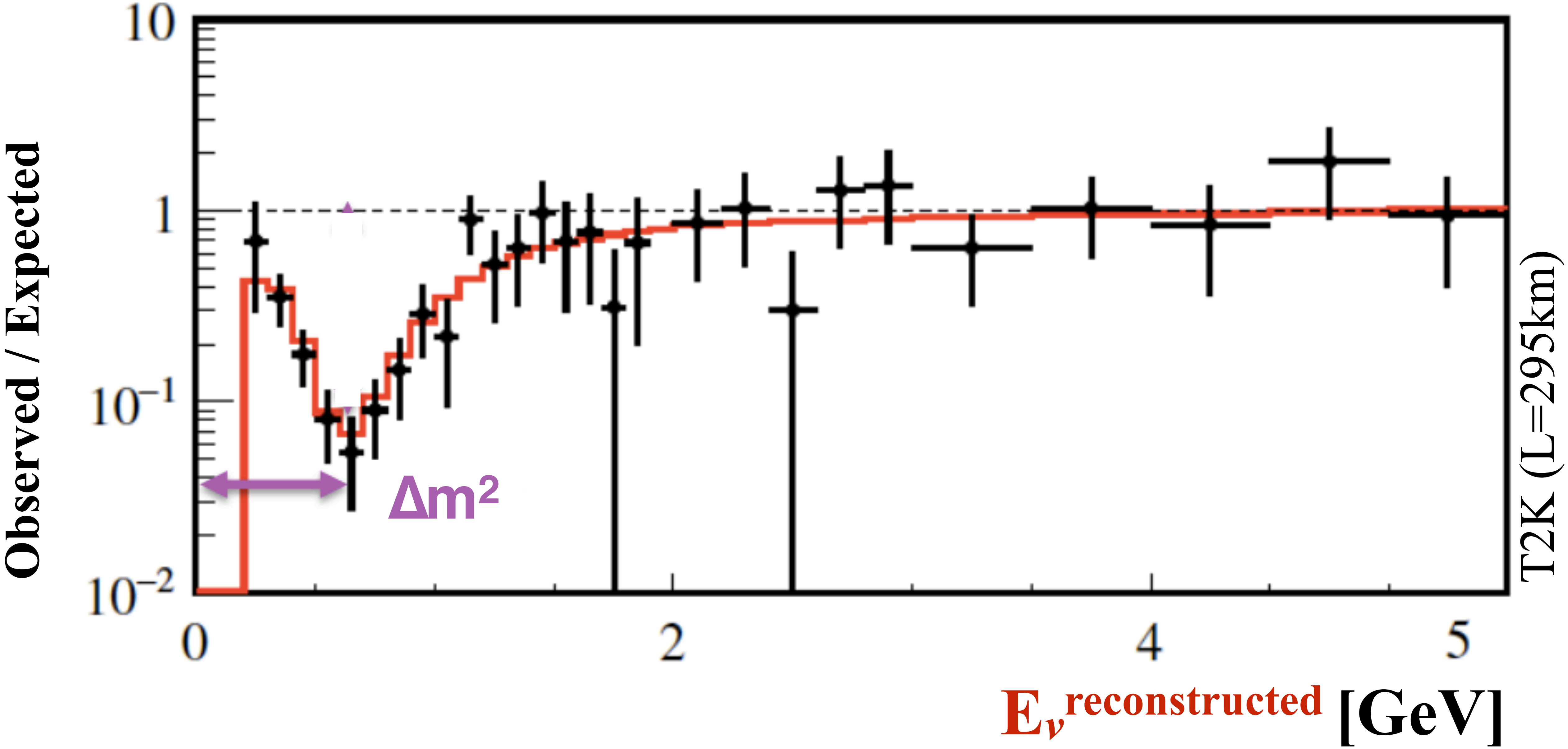
Oscillations Require E_ν Reconstruction

$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{real}}\right)$$



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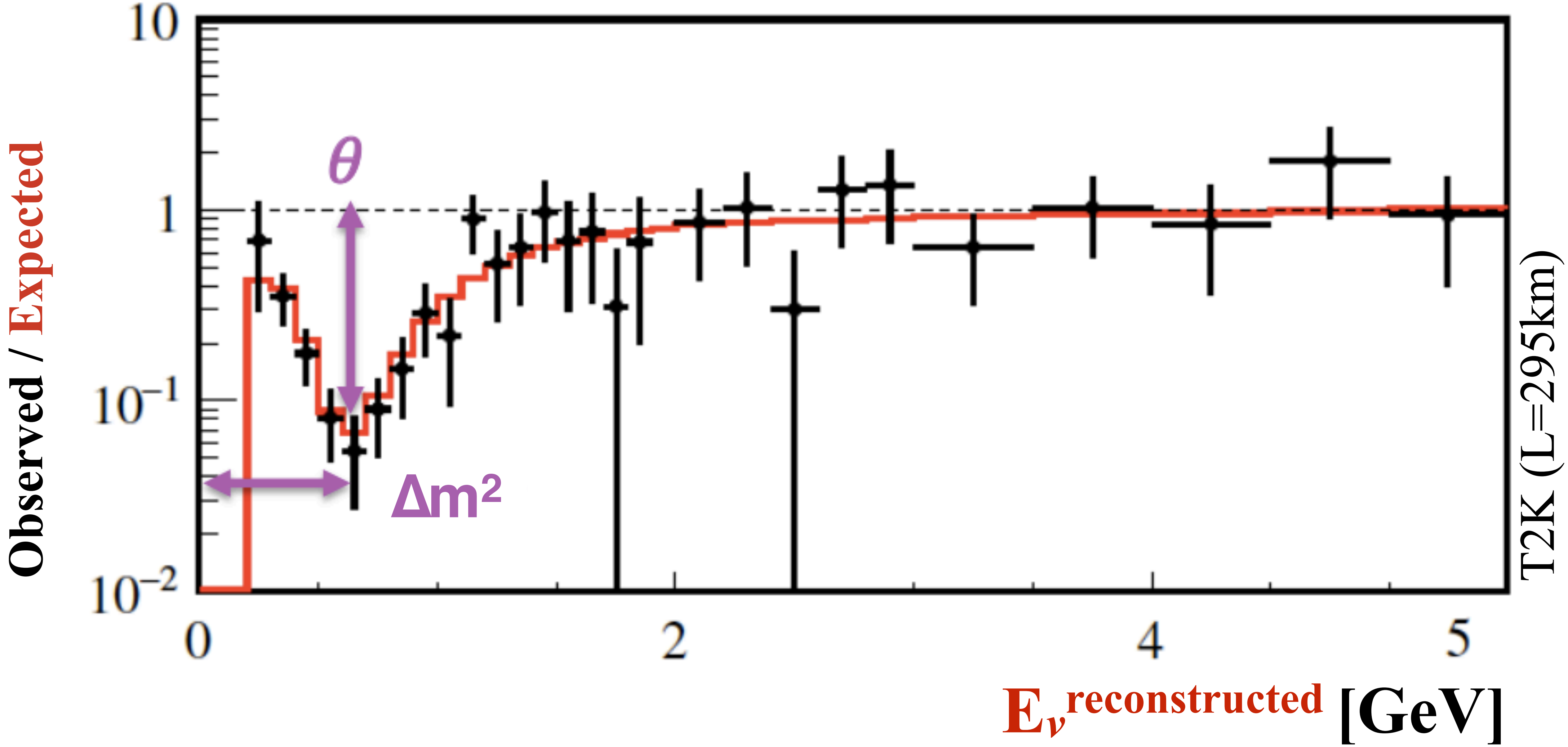
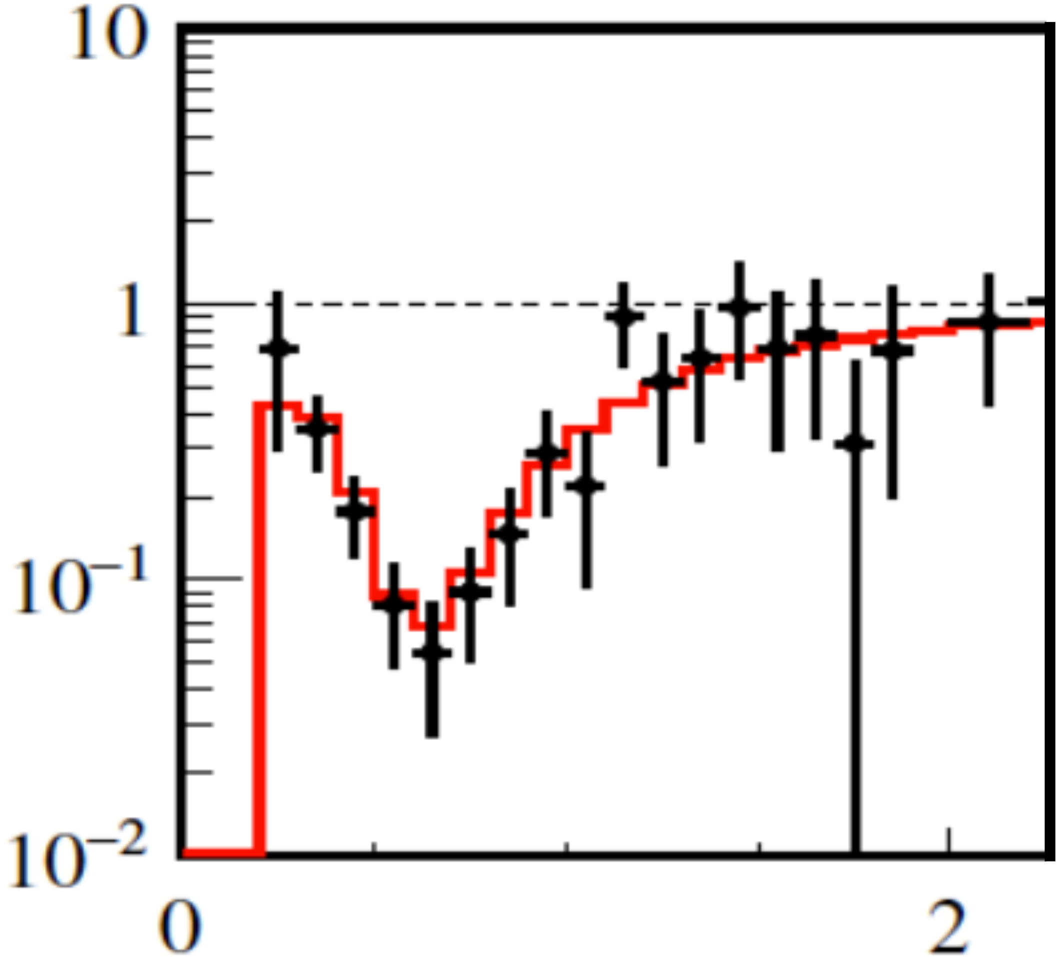


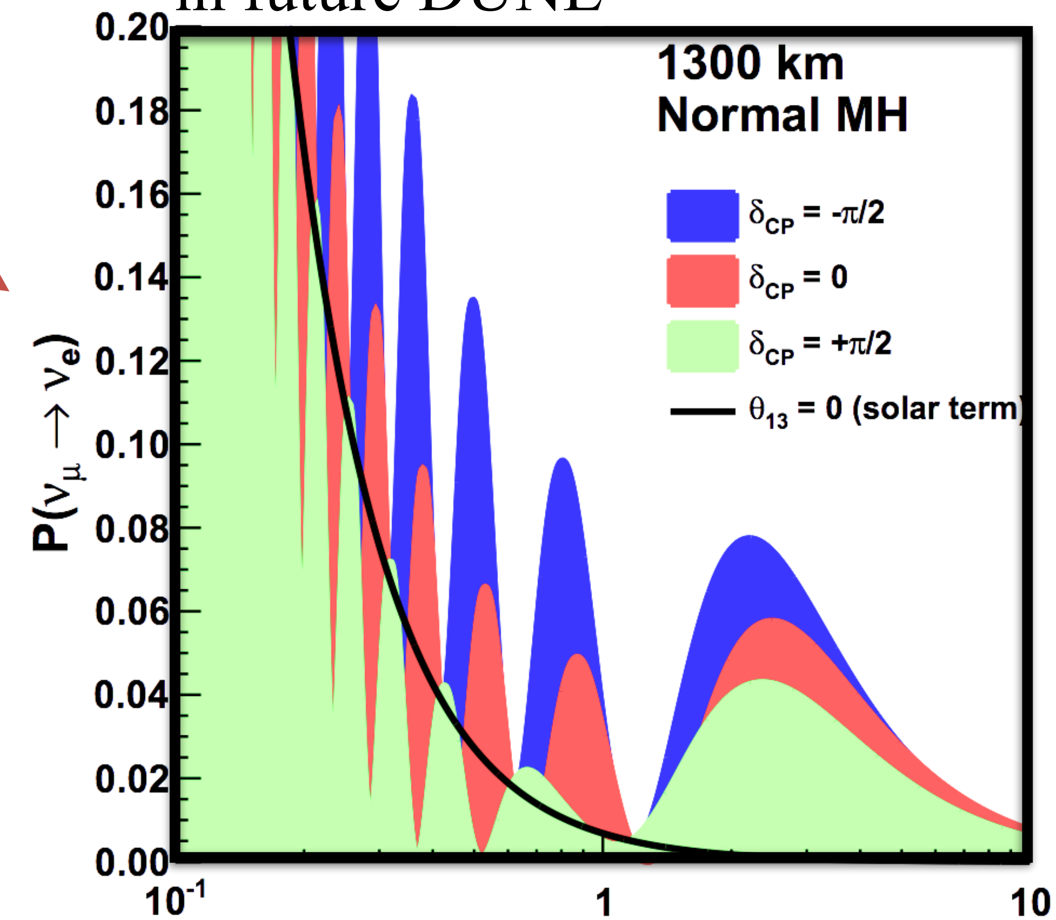
 T2K, Phys. Rev. D 91, 072010 (2015)

Next generation - High Precision Challenge



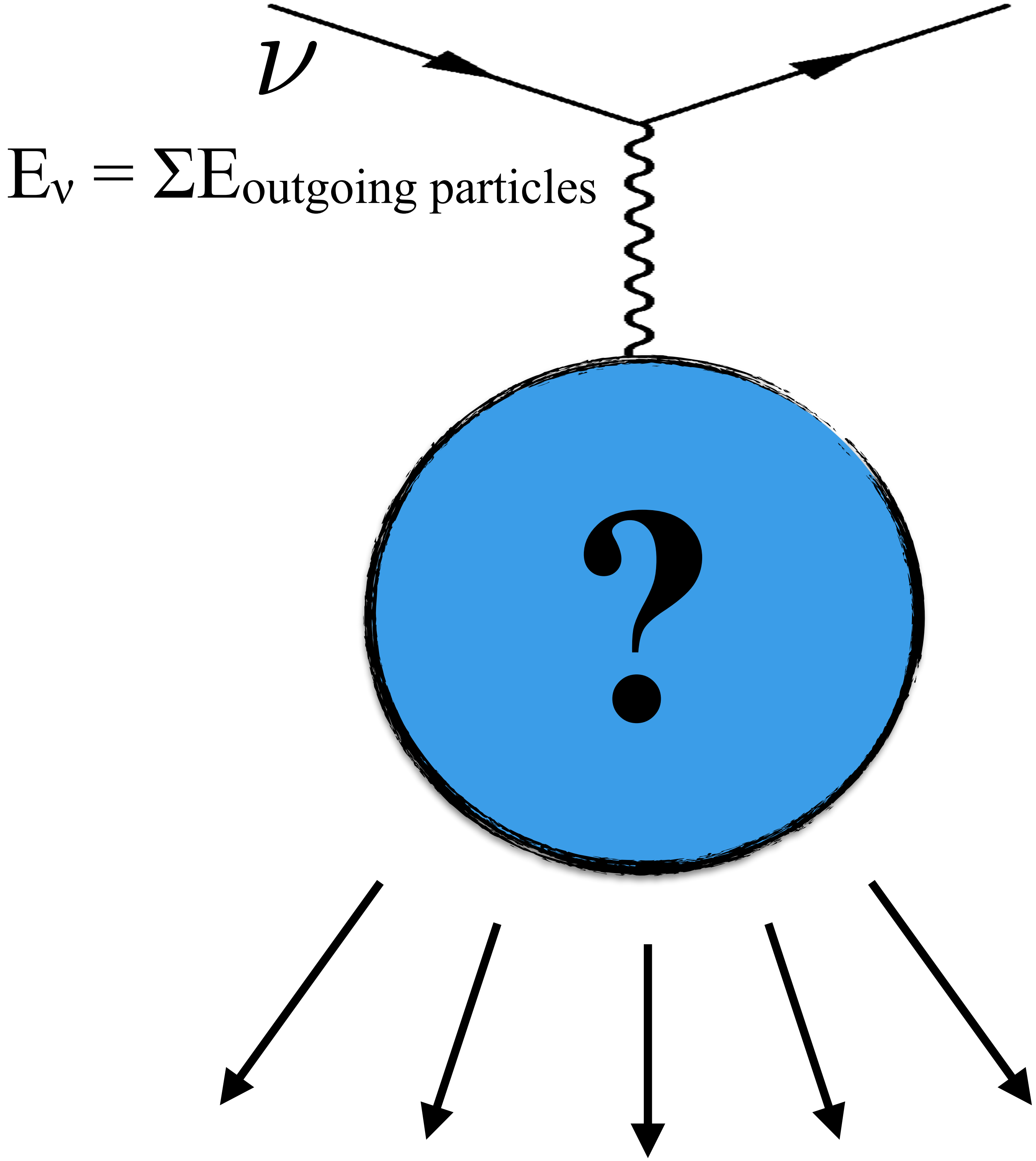
Neutrino Energy [GeV]

Simulation of oscillation effects in future DUNE

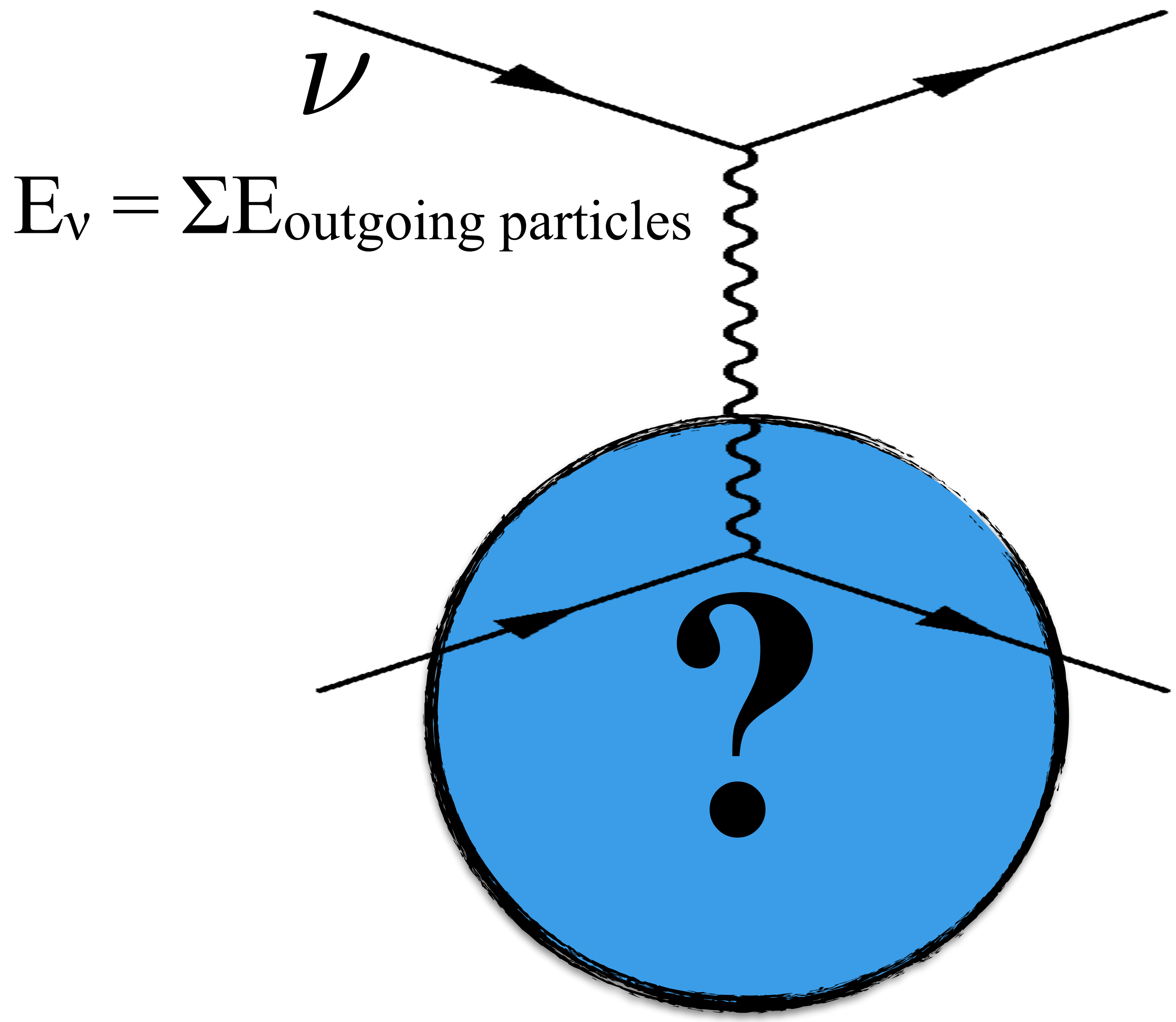


Neutrino Energy [GeV]

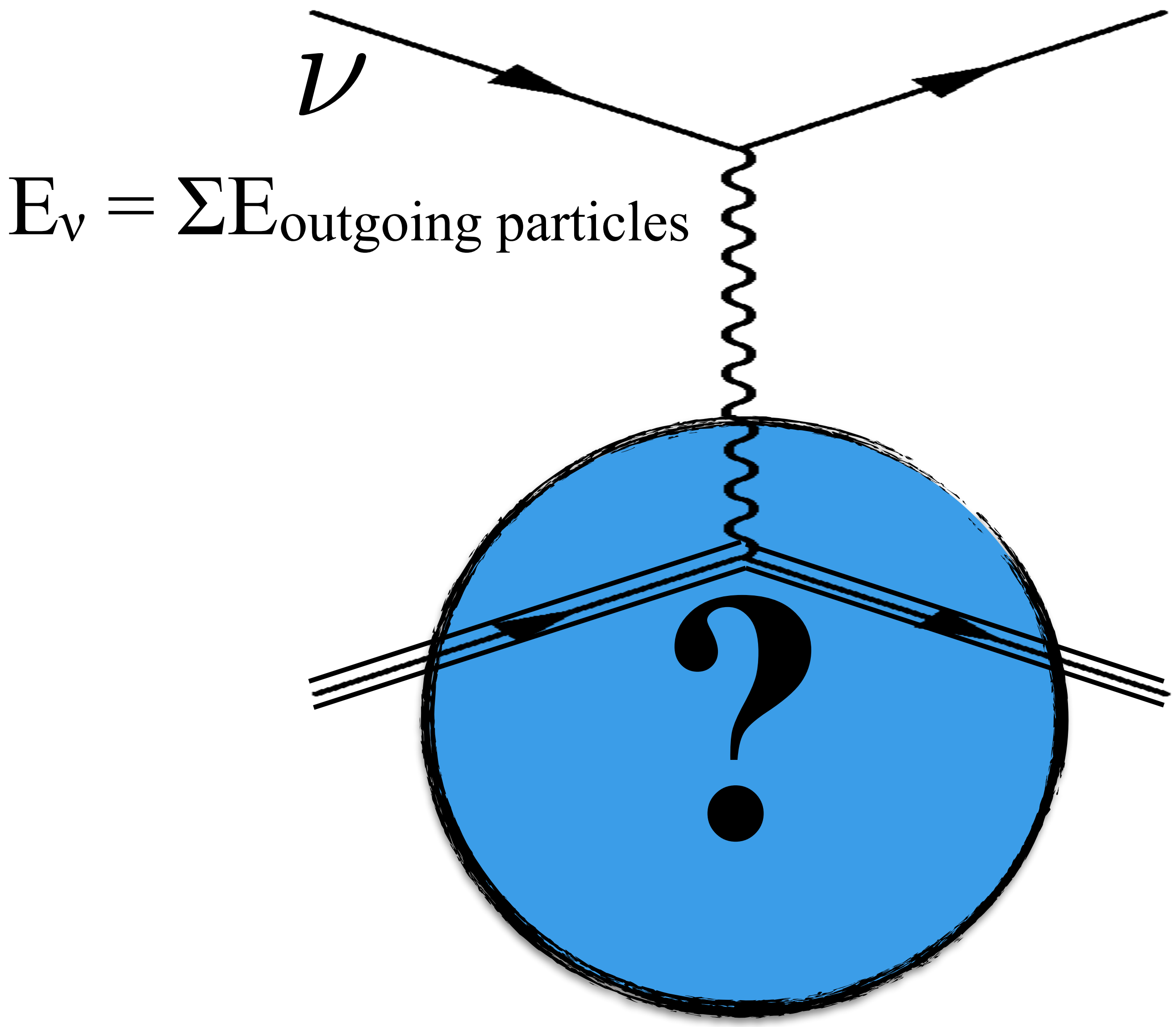
E_ν Reconstruction: Interaction Modeling



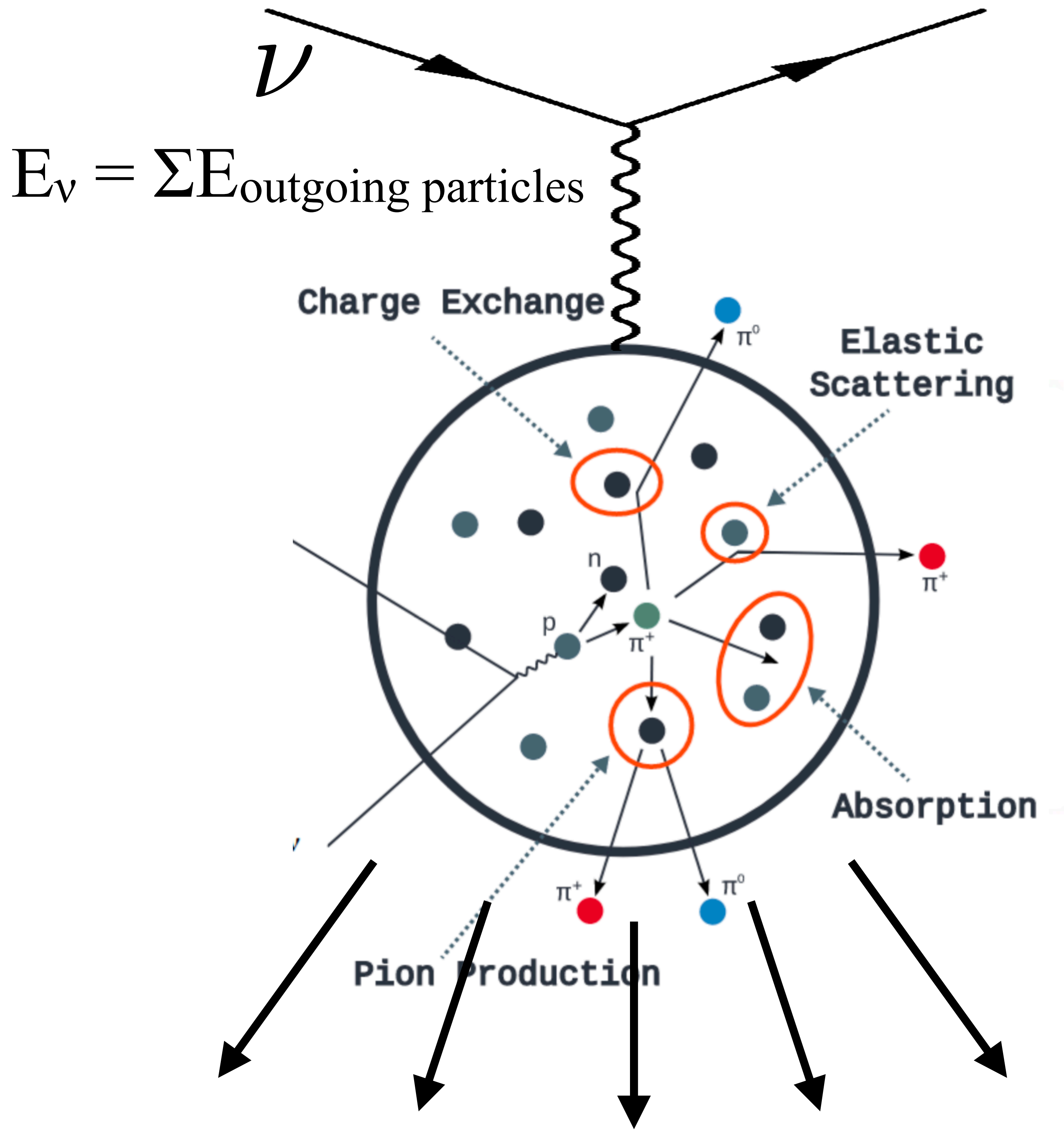
E_ν Reconstruction: Interaction Modeling



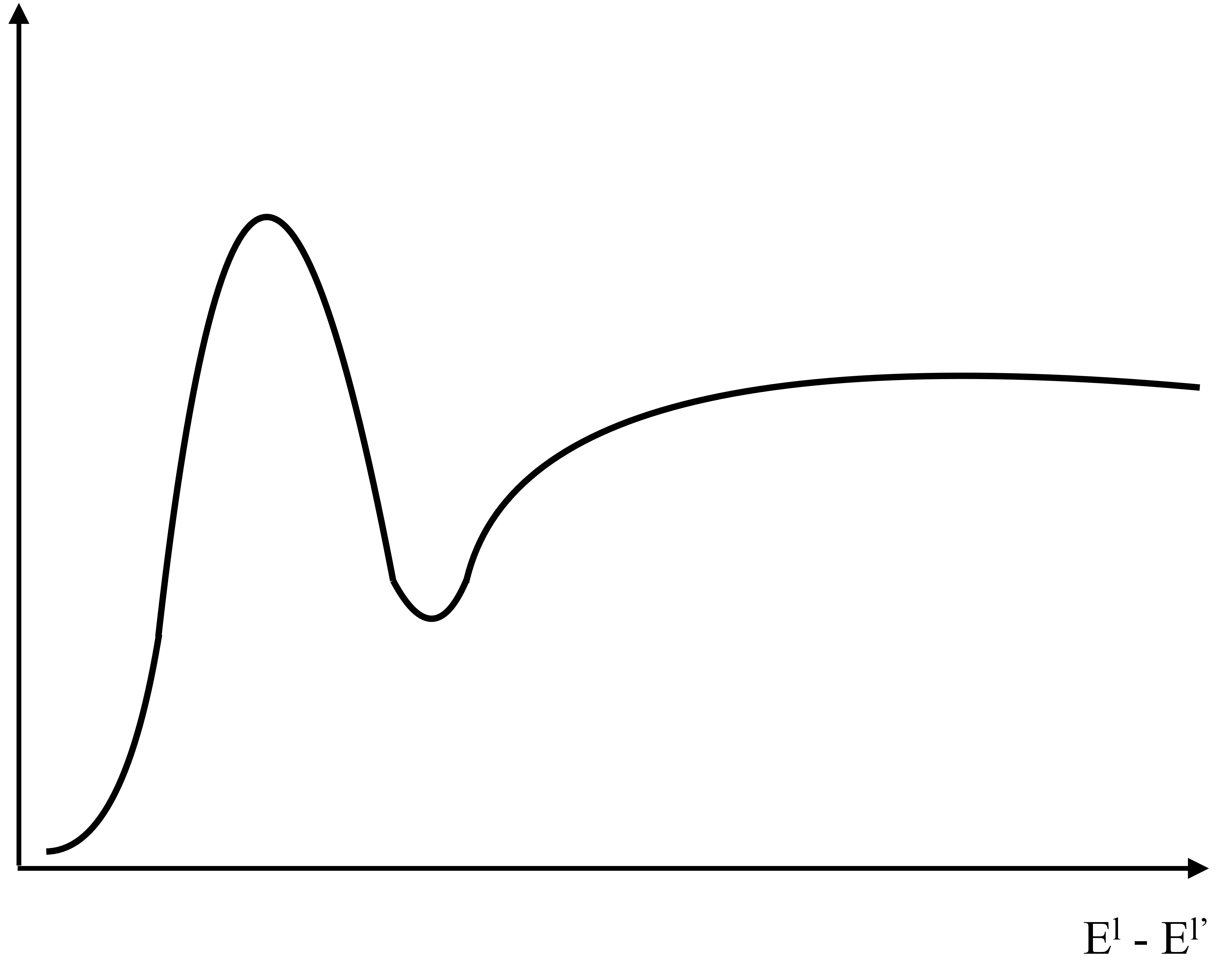
E_ν Reconstruction: Interaction Modeling



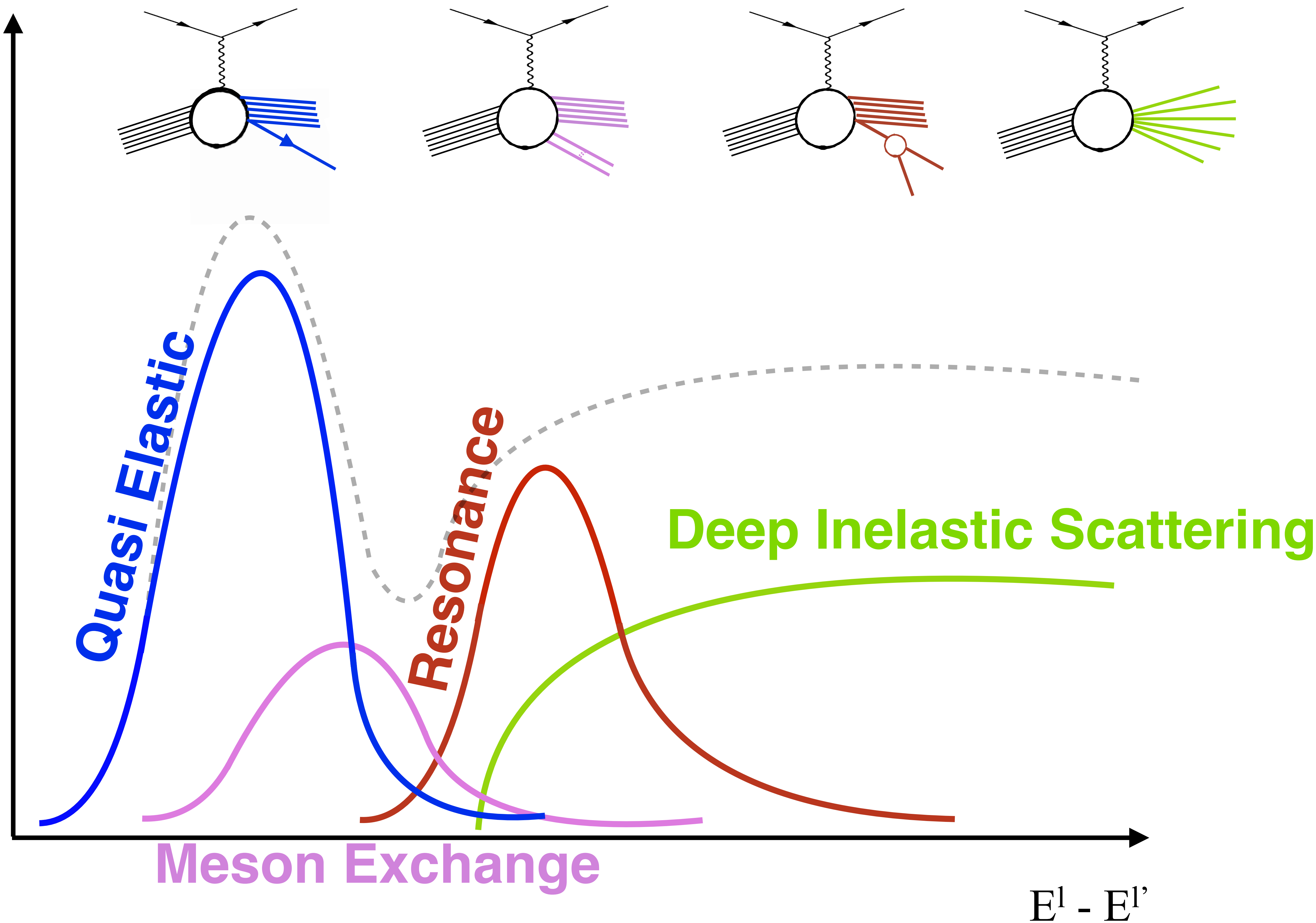
E_ν Reconstruction: Interaction Modeling



E_ν Reco Requires Interaction Modeling



E_ν Reco Requires Interaction Modeling



νA Interaction Modelling

Neutrino event generators are used to simulate a νA interaction

Among those:

Genie

GiBUU

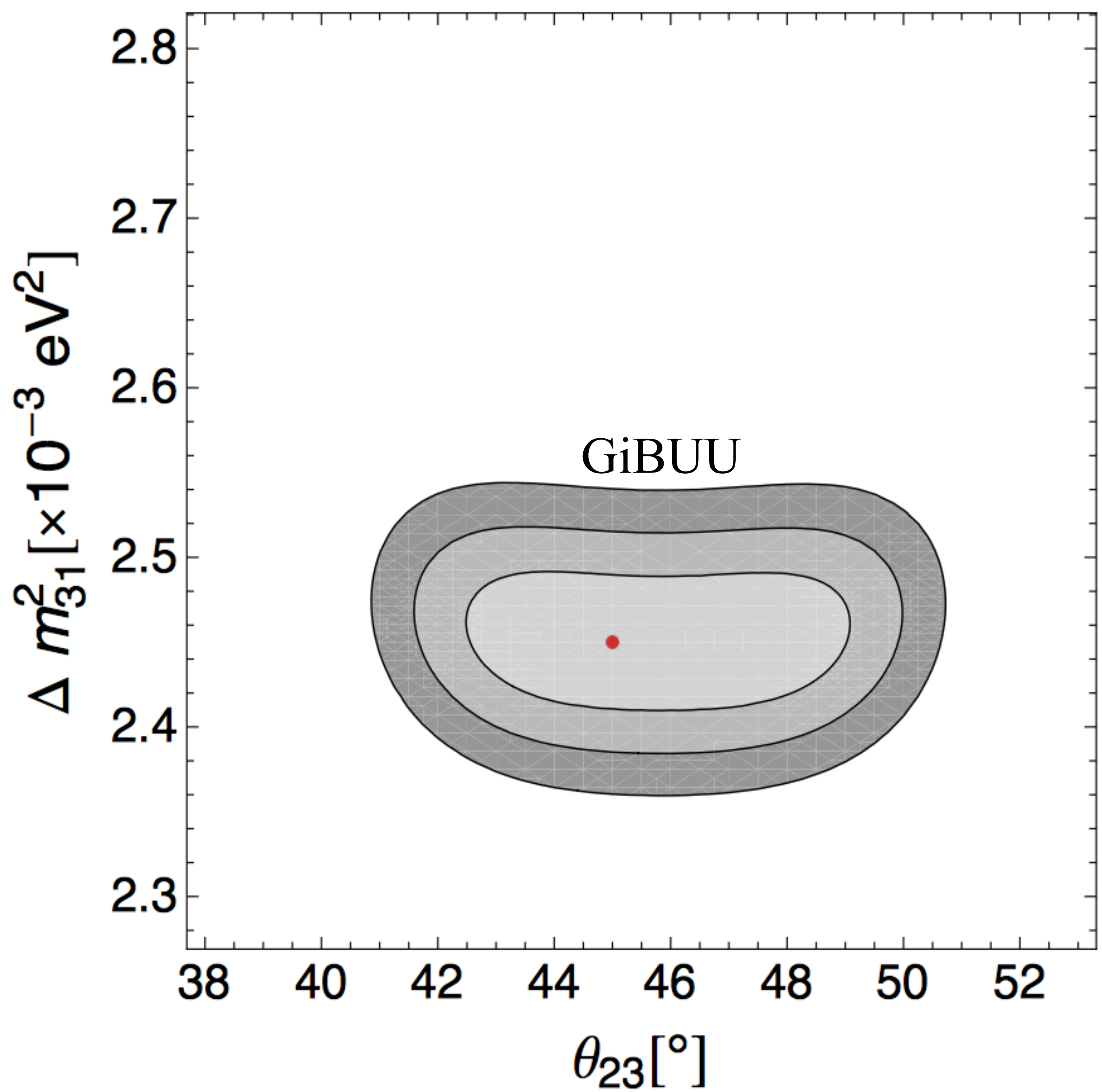
The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more

Semi classic, effective and data driven models

Have to be tuned to data

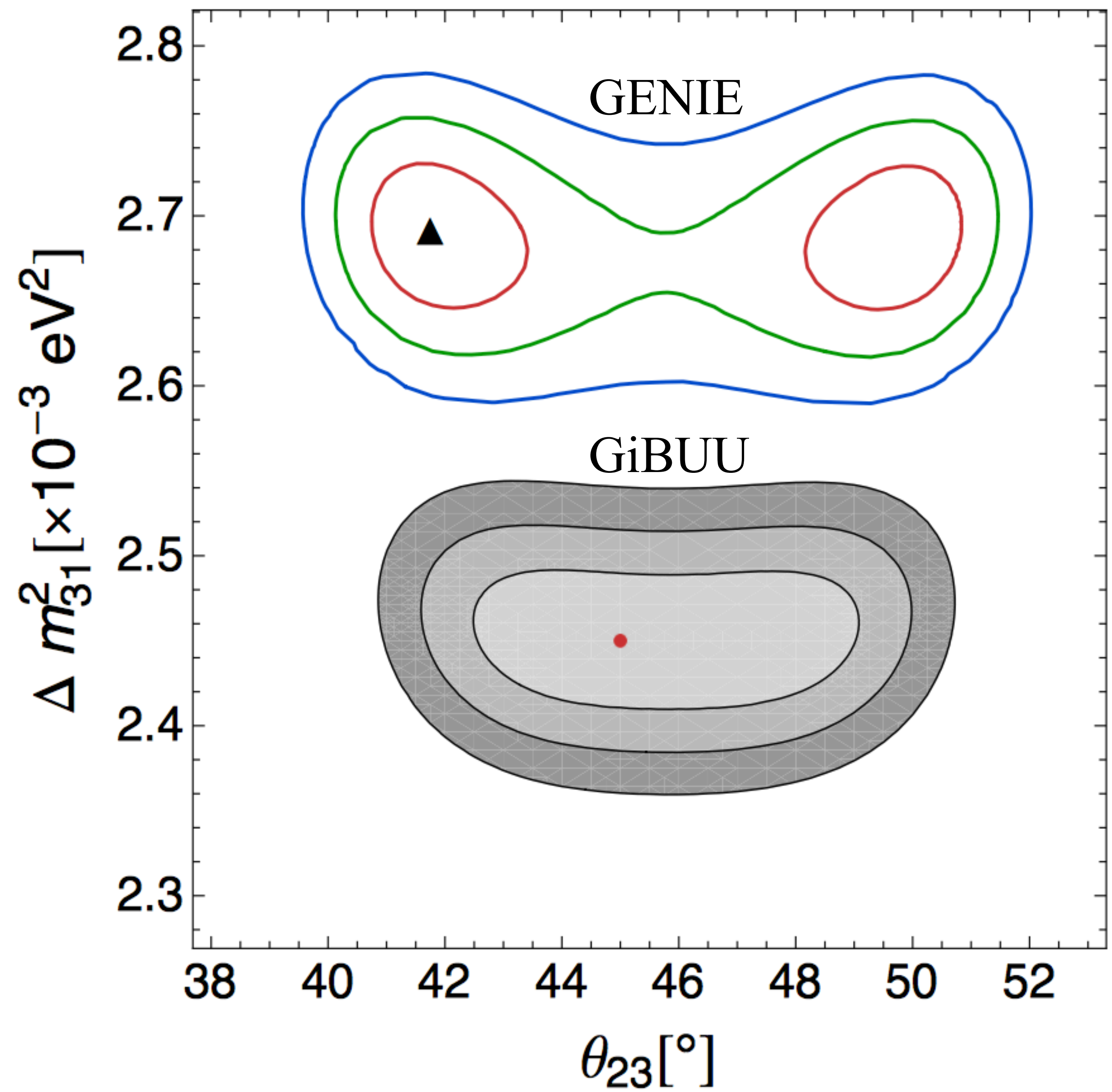
Nuclear Uncertainties are significant



Phys. Rev. D 89, 073015 (2014)

Nuclear Uncertainties are significant

Could lead to wrong extraction of the mixing parameters due to incomplete modelling of the nuclear physics involved.



Phys. Rev. D 89, 073015 (2014)

How to move forward

- Improved theory

- Use near detector
  - Wish to probe nuclear physics and no oscillation effects
  - Compare different models, tuned to the near detector data and take the spread as the uncertainty

- **External constraints on nuclear model**
  - **Compare theory to high precision electron scattering data**

- Electrons and Neutrinos have:
  - Similar interactions (vector vs. axial vector)
  - Very similar nuclear effects
    - Identical nuclear ground state (spectral function)
    - Final state interaction

Electron beam have known energy

$e4\nu$: Playing the Neutrino game

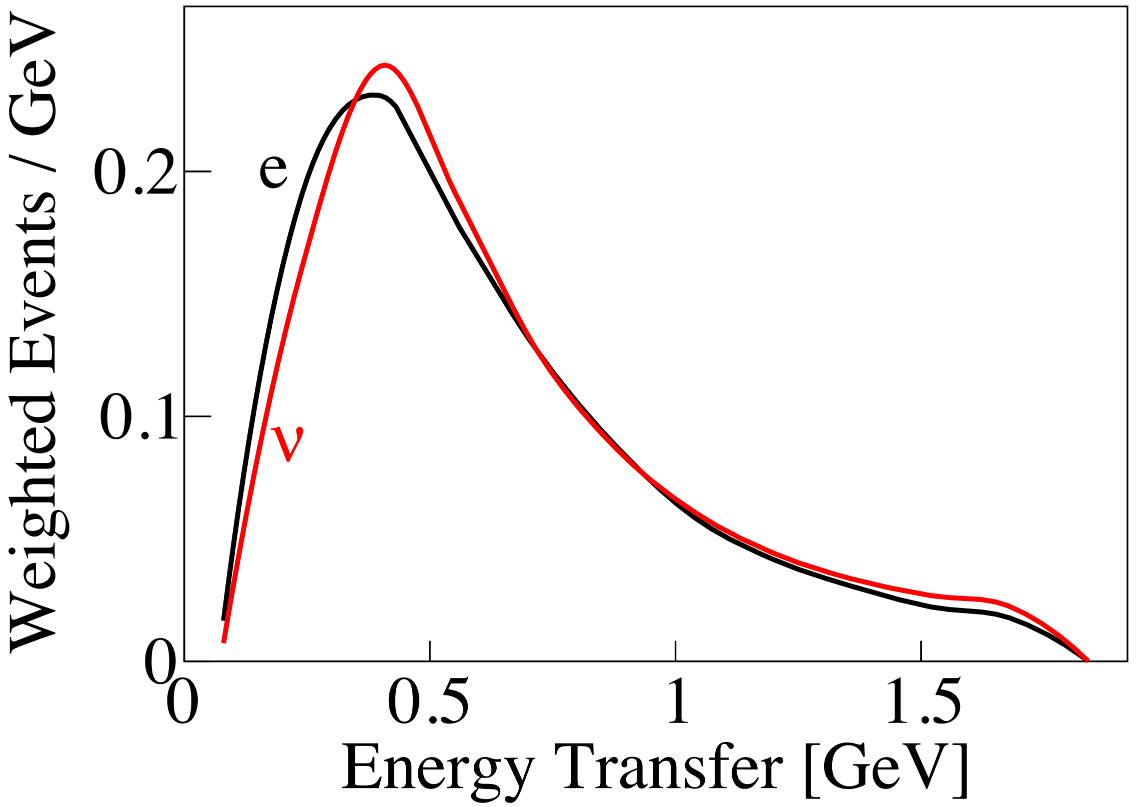
Let's analyse electron data as if it was 'Neutrino data'

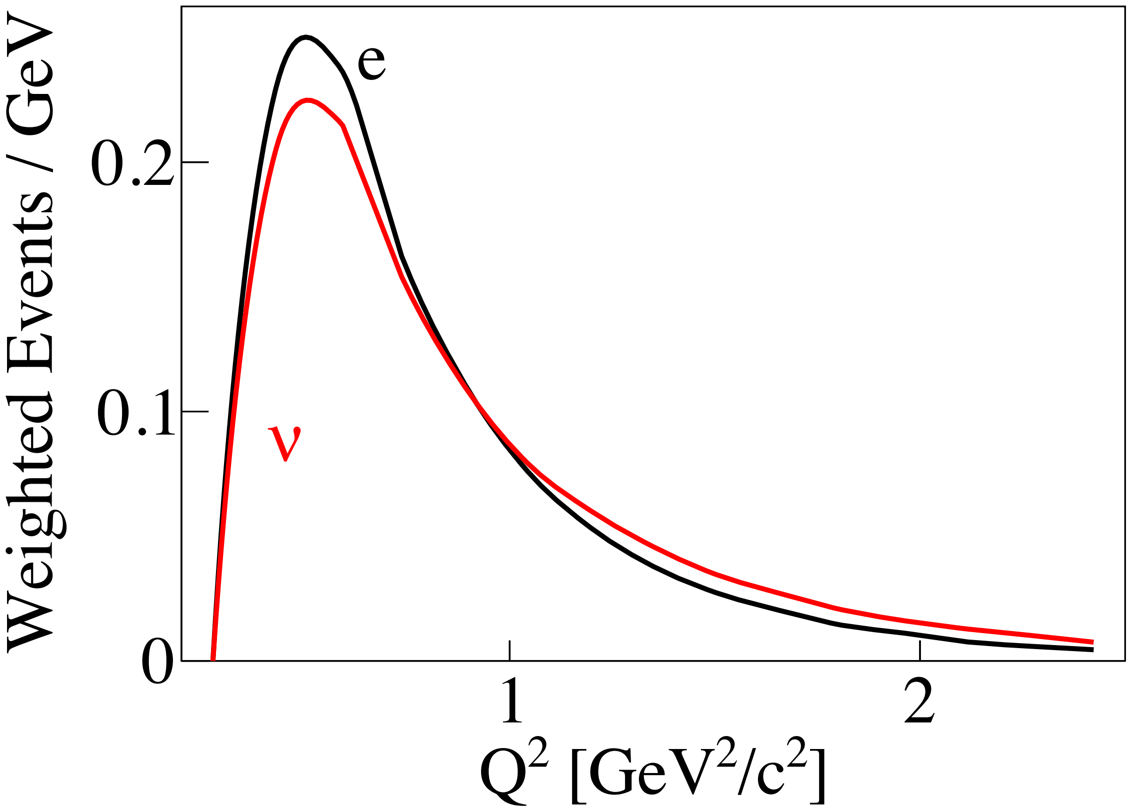
- Select a specific interaction
- Scale the electron data by $1/Q^4$
- Reconstruct the incoming neutrino energy
- Compare to event generators

e4ν: Playing the Neutrino game

Comparing similar interactions with neutrinos and electrons

Electron interaction are weighted by $1/Q^4$





^{56}Fe E = 2.2 GeV

CLAS Detector

Electron beam with energies up to 6 GeV

Large acceptance

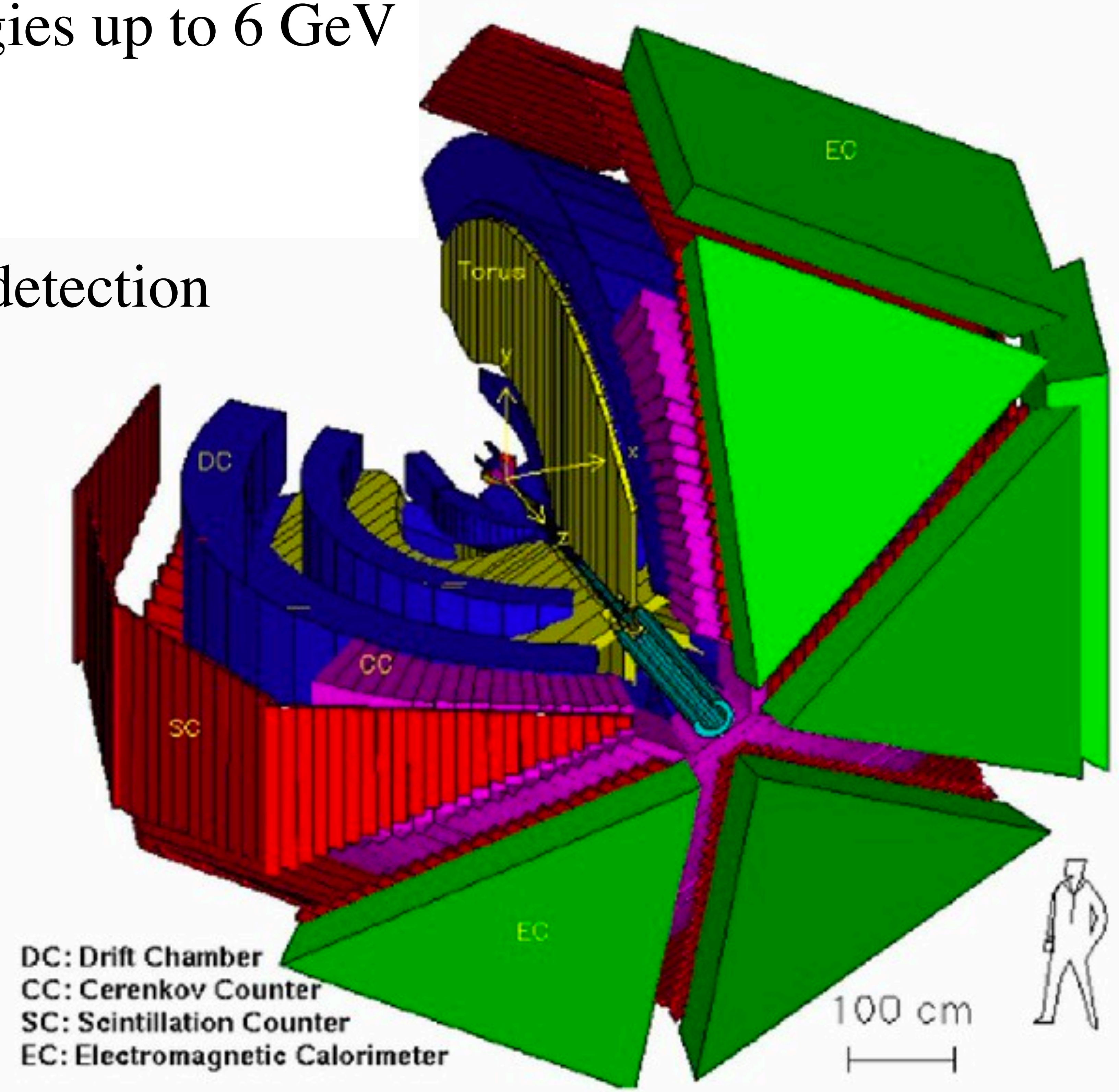
Charged particles above detection threshold:

$\theta_e > 15^o$

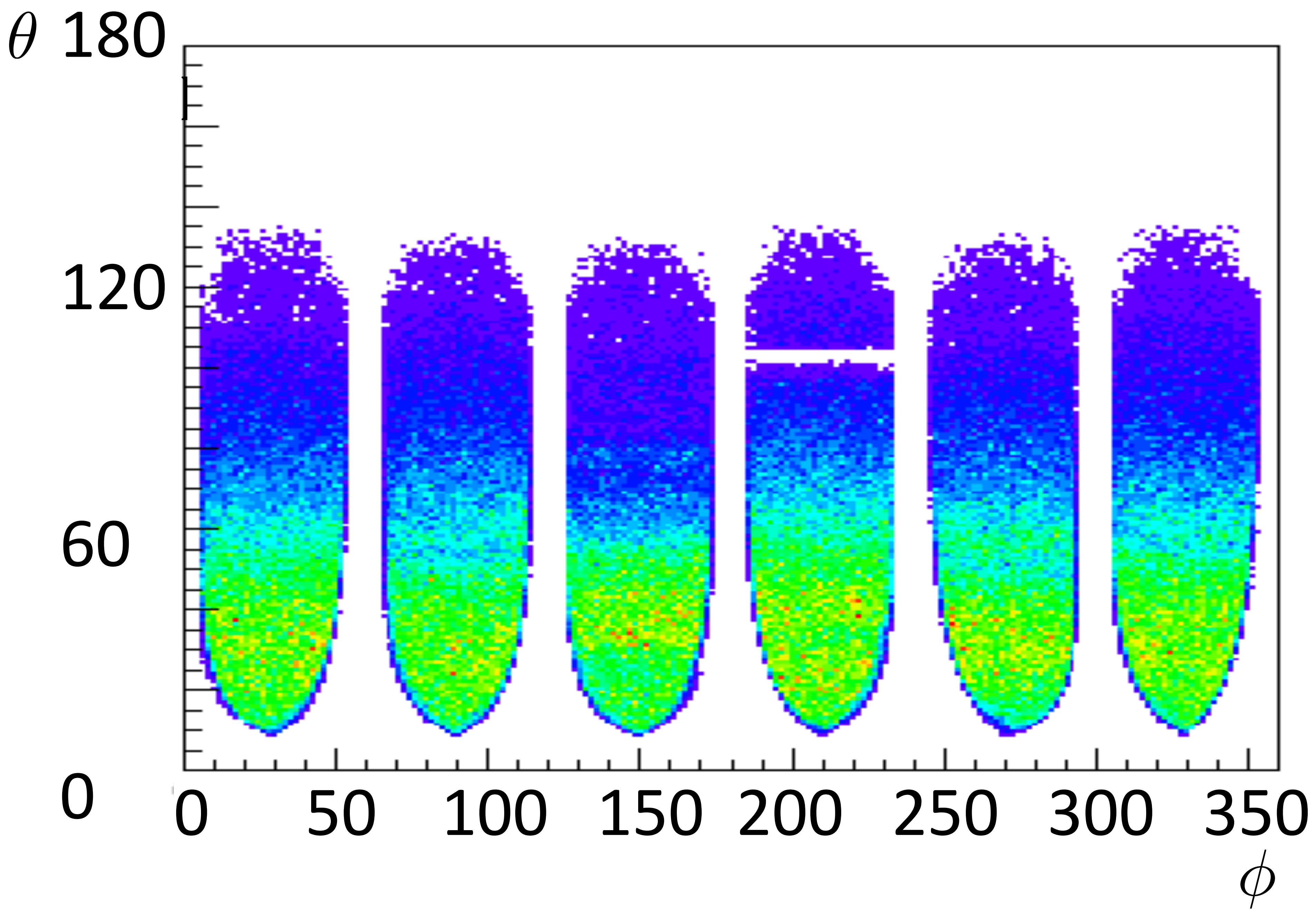
$P_p > 300$ MeV/c

$P_{\pi+/-} > 150$ MeV/c

Open Trigger



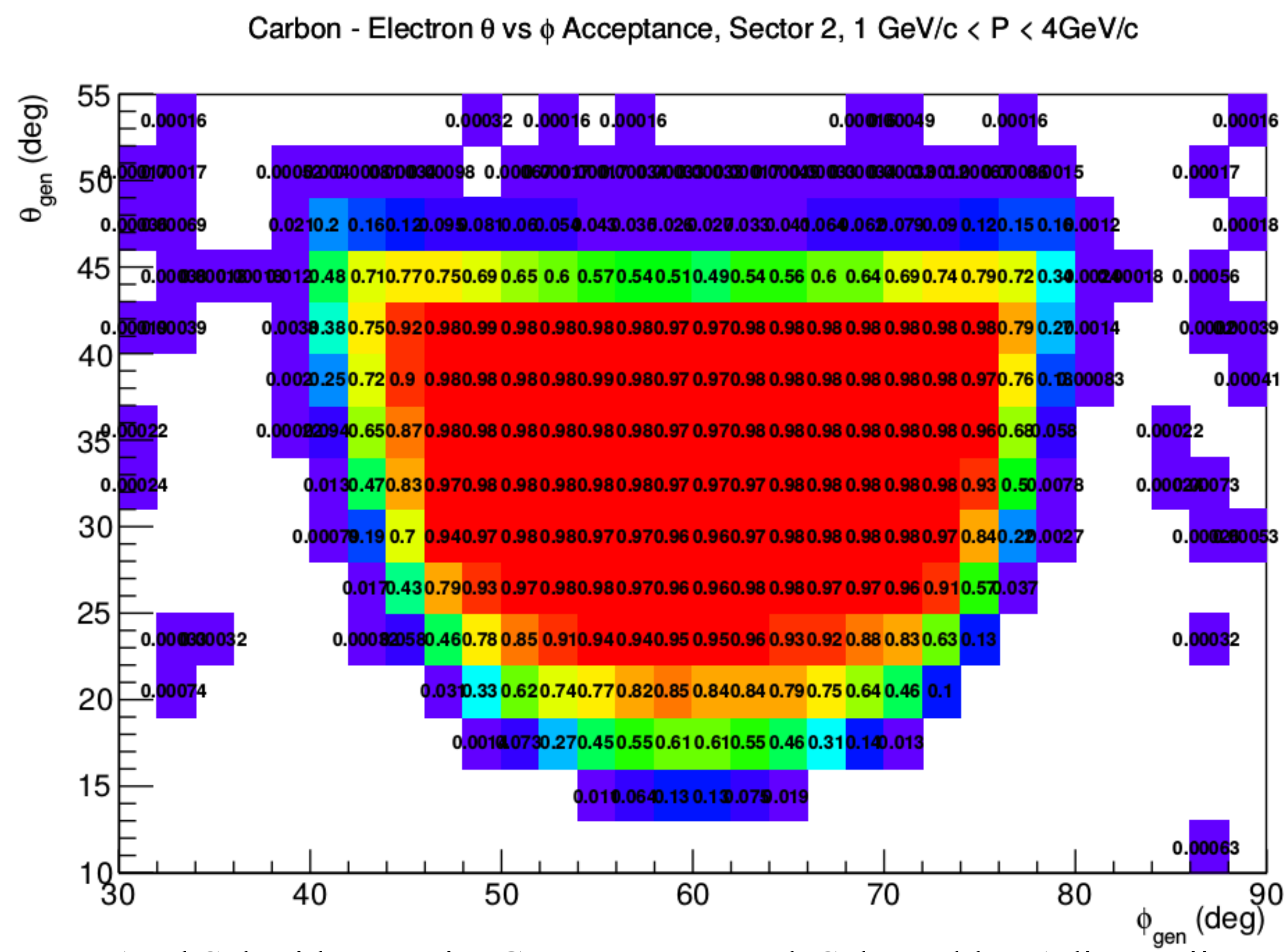
Wide Phase Space



CLAS: Acceptance maps availble

CLAS has a different efficiency, which we will publish as acceptance maps for public use for each:

- Target
- Particle type
- Particle momentum



Axel Schmidt, Reynier Cruz Torres, Barak Schmookler, Adin Hrnjic

CLAS A(e,e'p) Data

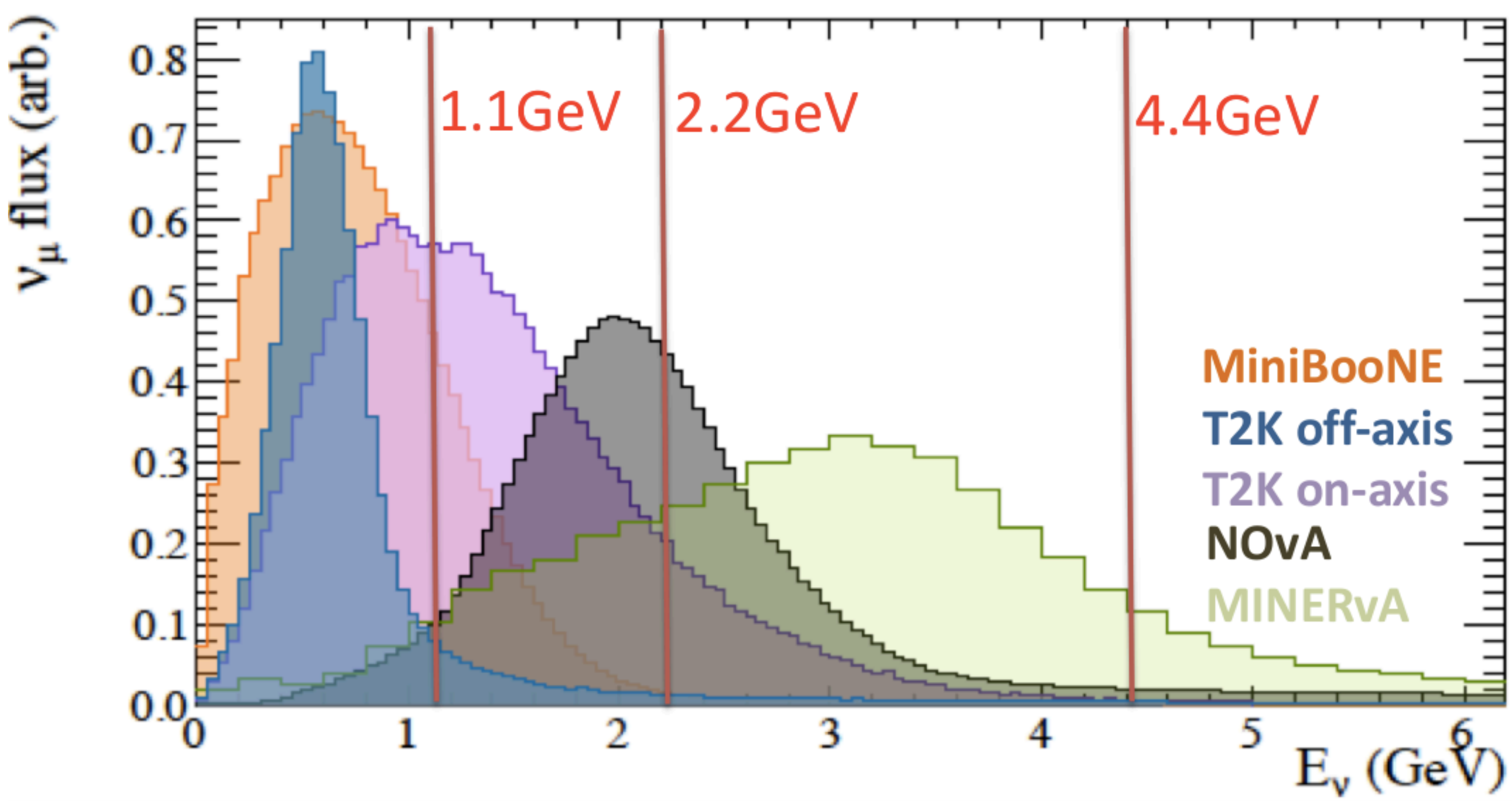
Targets:

^{4}He, ^{12}C, ^{56}Fe

T2K	H_2O
NOvA	CH
SBN Program, DUNE	Ar

Energies:

1.1, 2.2, 4,4 GeV



e4ν A(e,e'p) Event Selection

Focus on QE events:

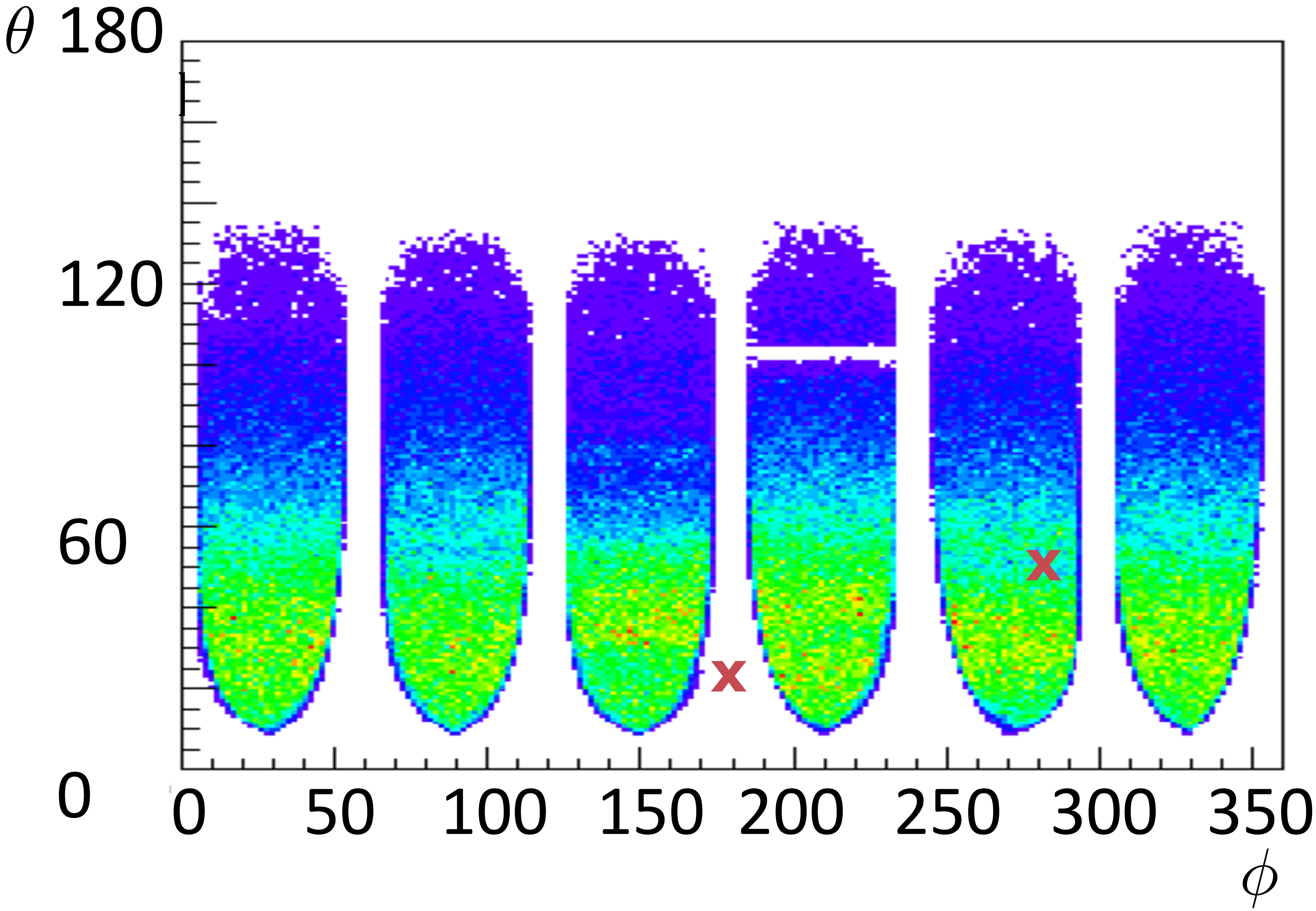
1 proton above 300 MeV/c

no additional charged hadrons above threshold

Background Subtraction

Different interaction lead to multi-hadron final states

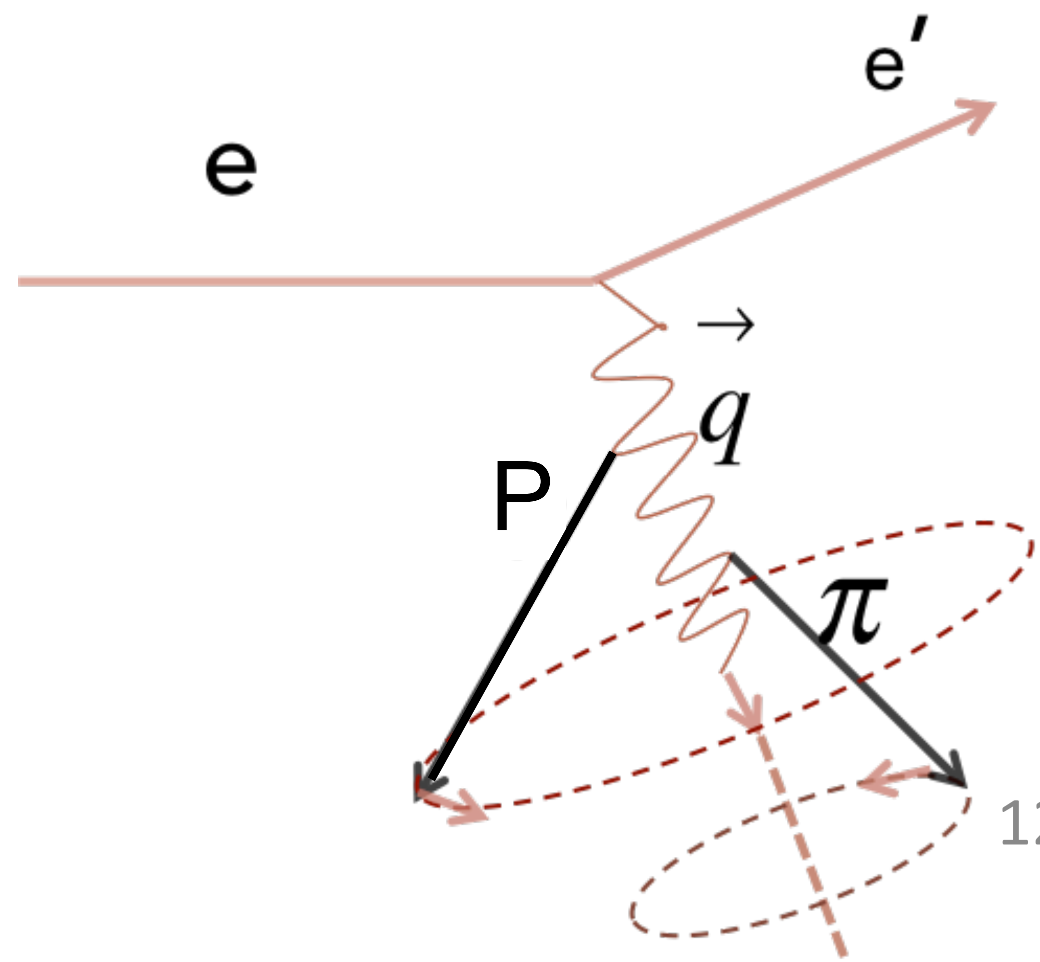
Gaps can make them loop like QE-like events with outgoing 1μ1p



Data driven Background Subtraction

- Using events with two hadrons,
- Rotating p,π around q and determine π detection efficiency
- Subtract contribution to QE-like

Same for final states with more than 2 hadrons



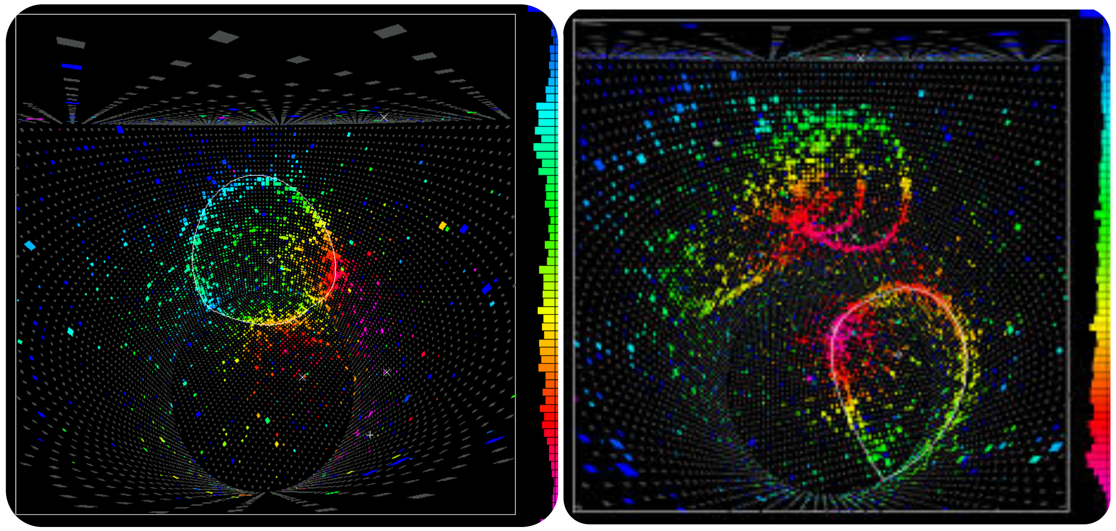
12

Incoming neutrino Energy Reconstruction

$$N(E_{rec}, L) \propto \int \Phi(E, L)\sigma(E) f_{\sigma}(E, E_{rec}) dE$$

Incoming neutrino Energy Reconstruction

$$f_\sigma(E, E_{rec})$$

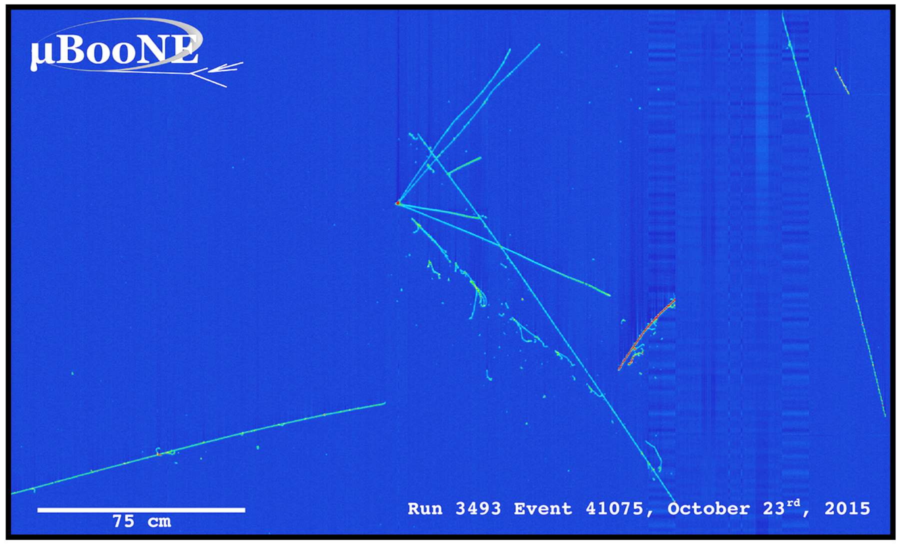


Cherenkov detectors:

Assuming QE interaction

Using solely the final state lepton

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$



Tracking detectors:

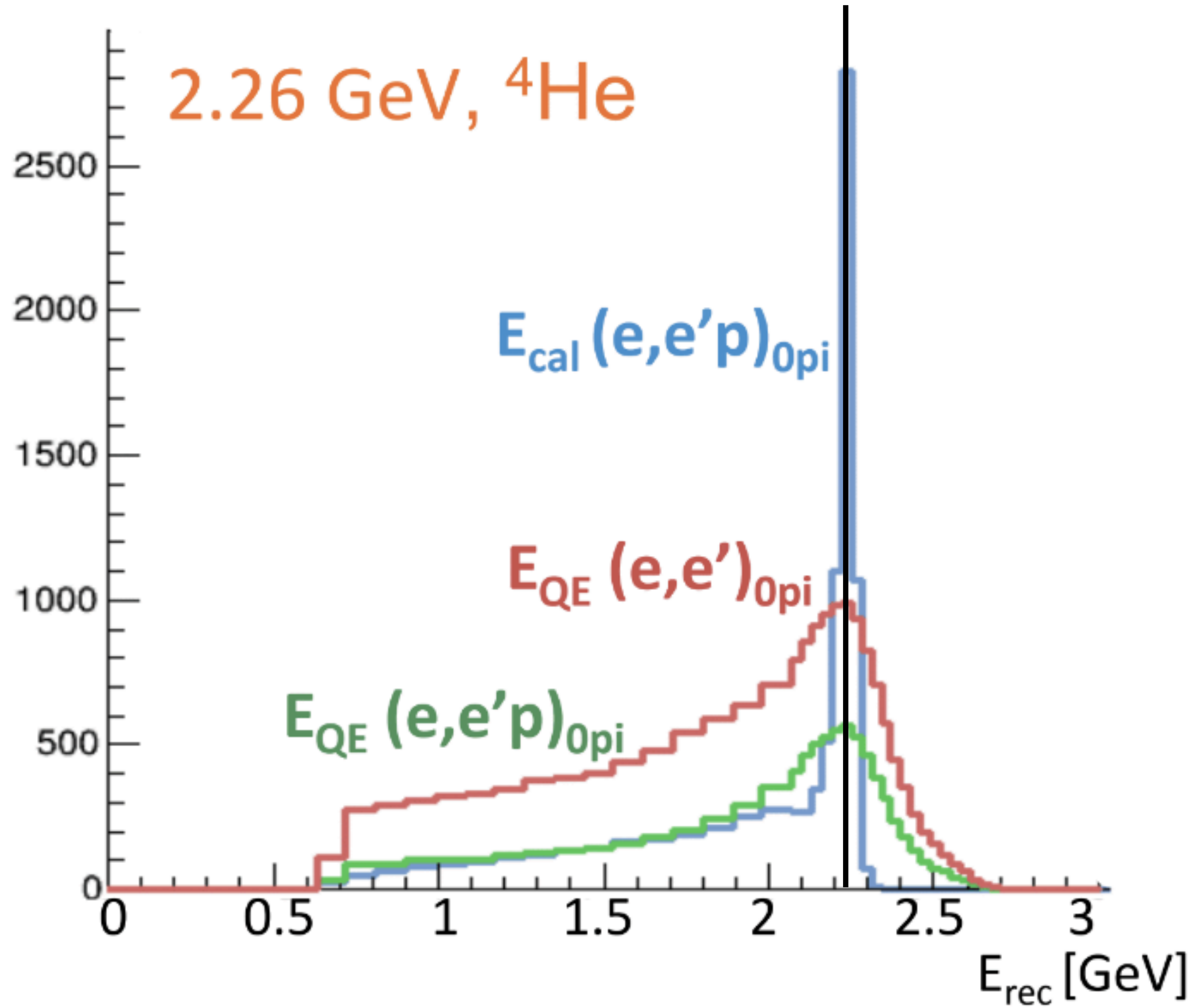
Need good hadronic reconstruction

$$E_{\rm cal} = E_l + E_p^{\rm kin} + \epsilon$$

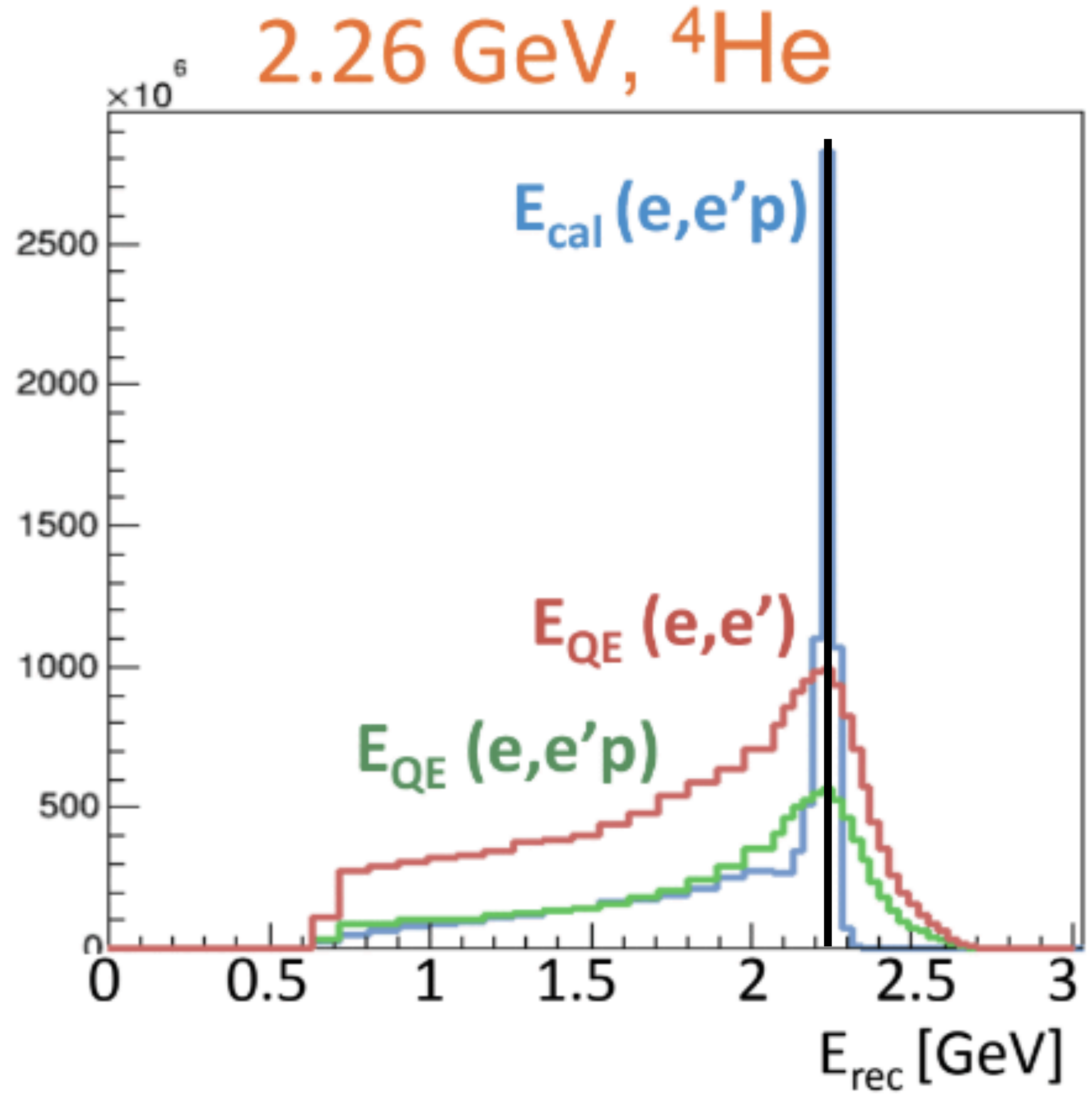
ϵ is the nucleon separation energy ~ 20 MeV

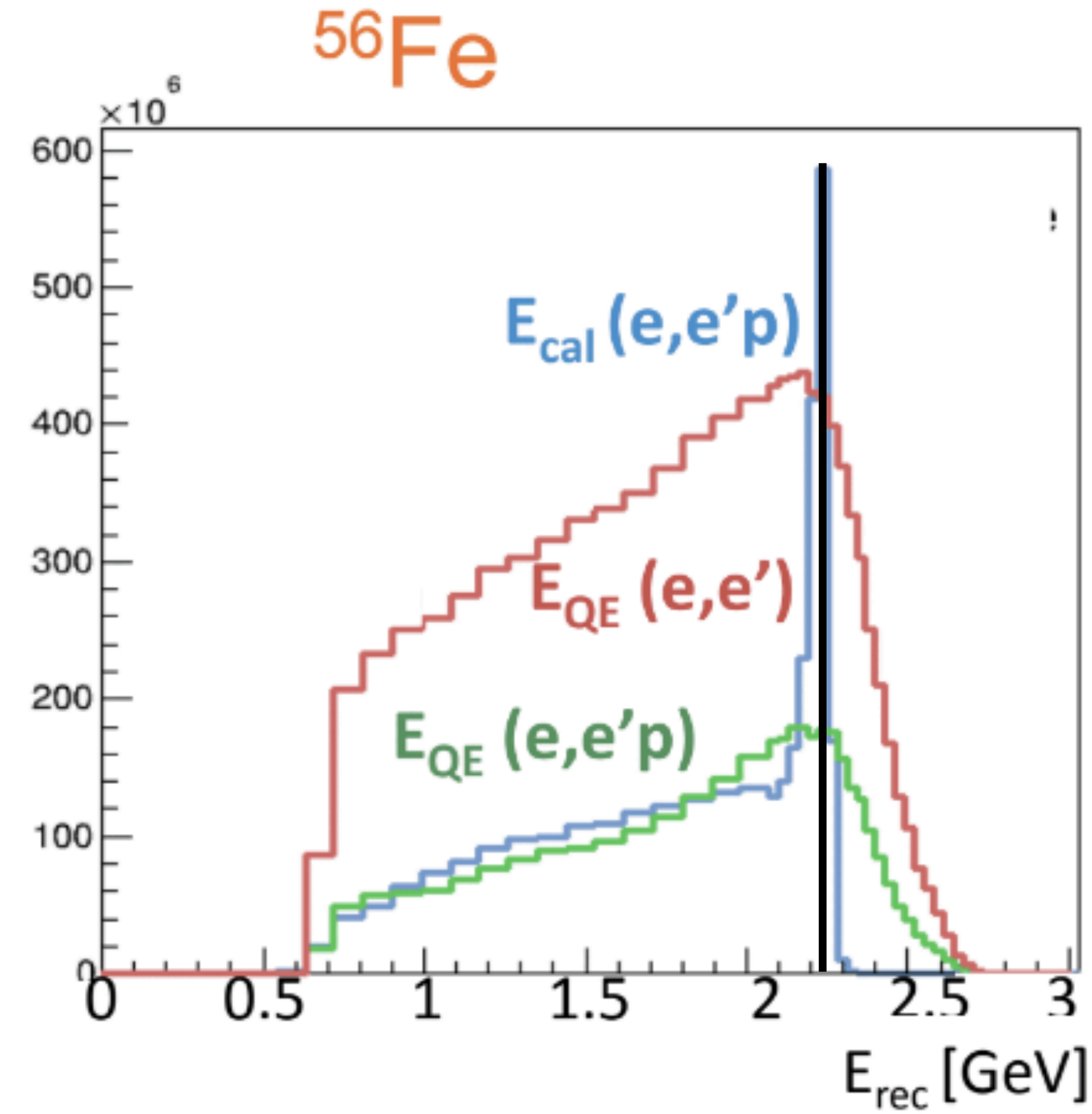
First look at the data

Testing the incoming energy reconstruction

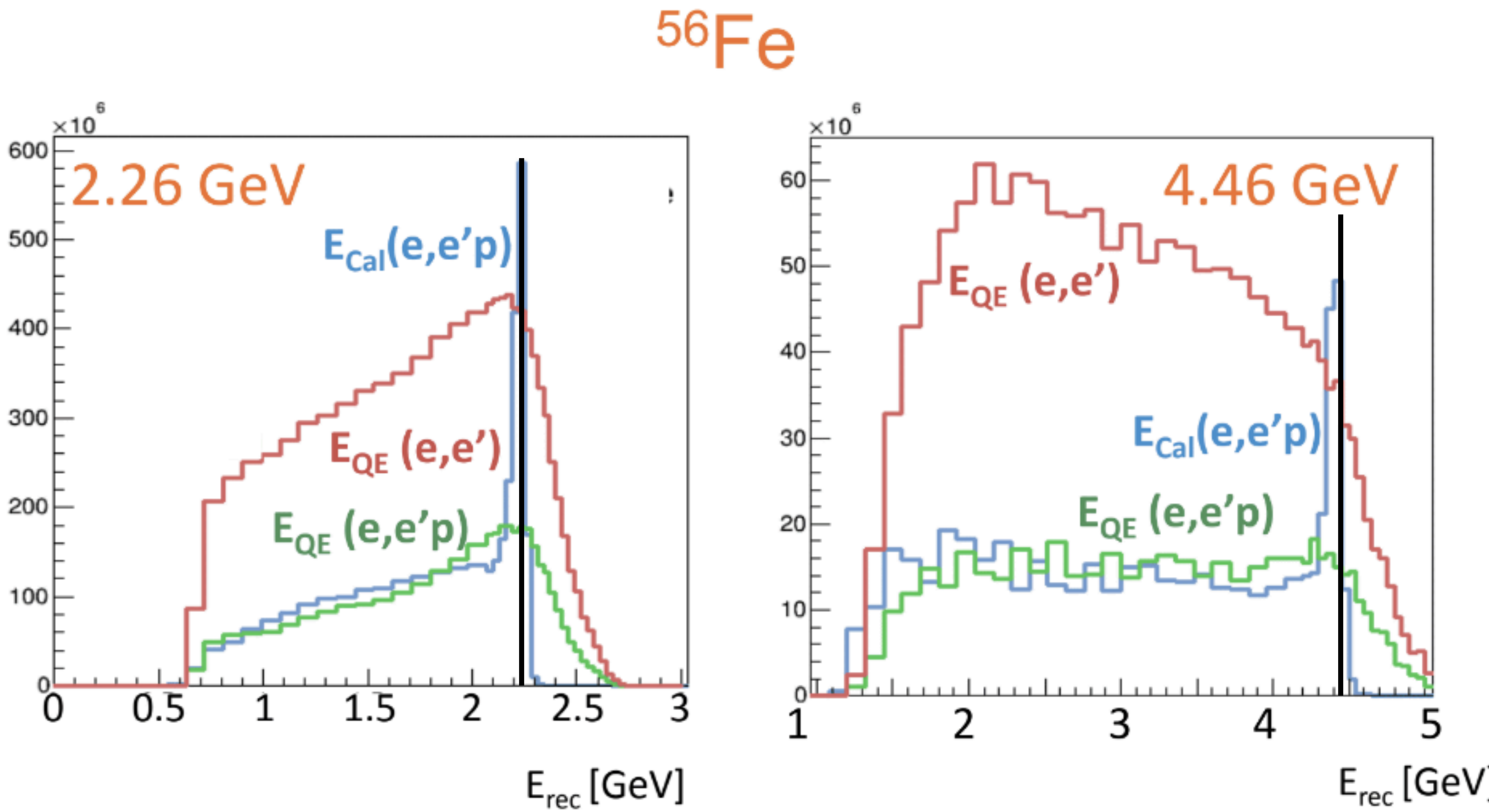


E_{rec} Worse with Higher Mass Number





E_{rec} Worse with Higher Energy



Simulation

GENIE Simulation

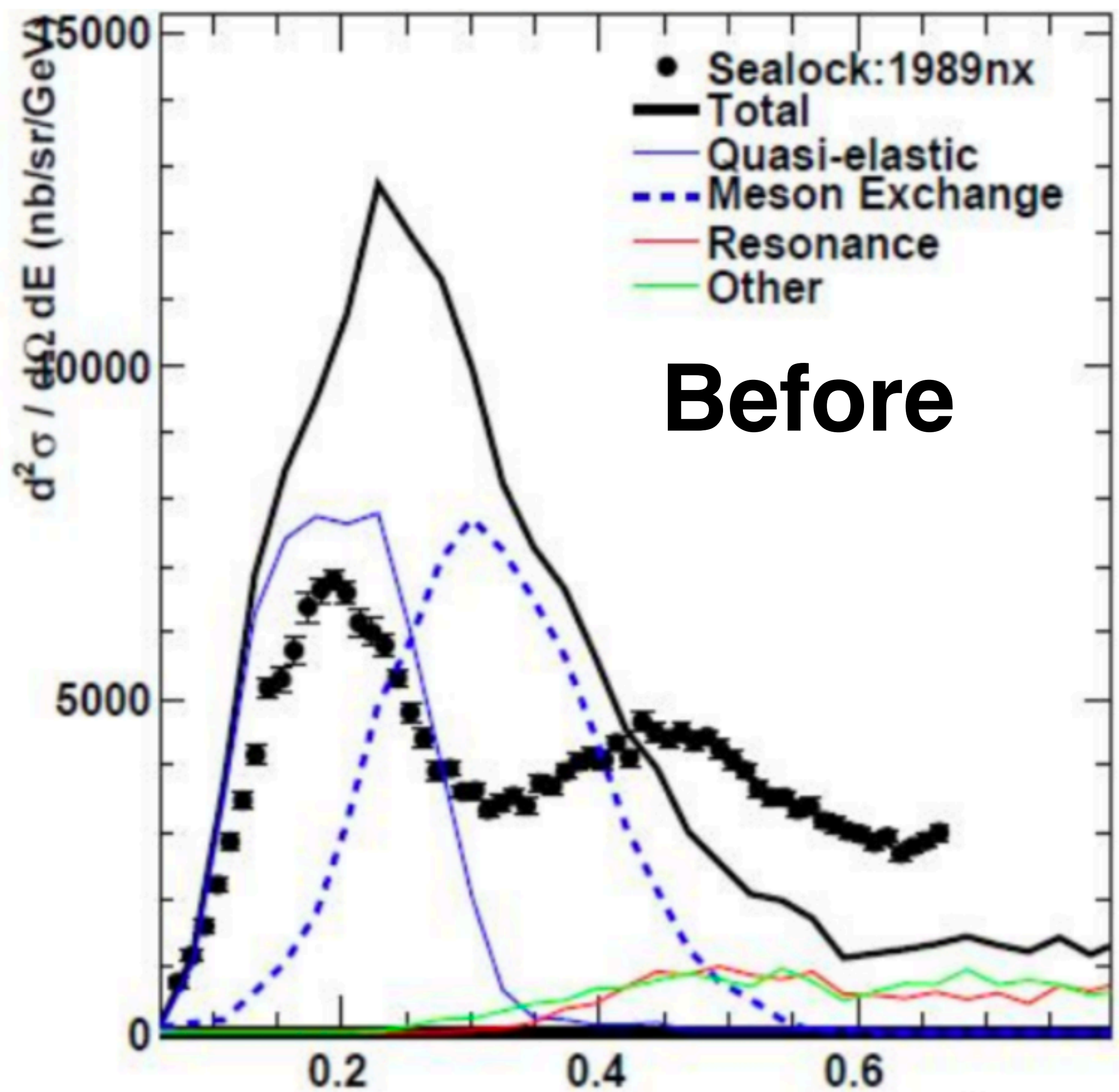
GENIE v2_12_10

Nuclear model	Local fermi gas model
QE	Lewellyn Smith for neutrino
	Rosenbluth CS for electrons
MEC	Empirical Dytman model
Resonances	Berger Sehgal
FSI	hA (data driven)

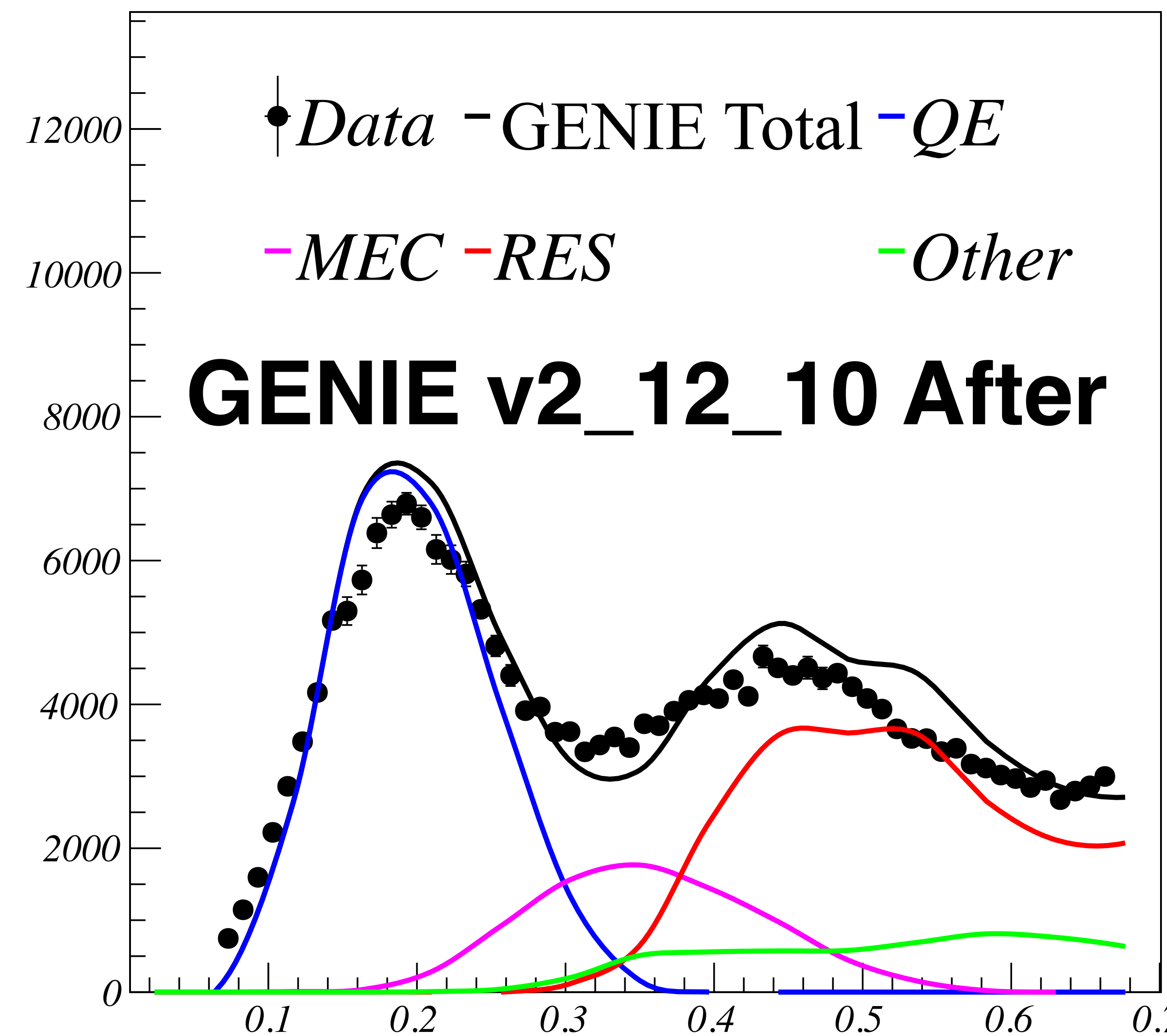
Adding radiative correction

Testing neutrino generators with inclusive electron scattering data

12C(e,e') E = 0.961 GeV $\theta = 37.5^\circ$



E^{l}-$E^{l'}$ [GeV]



E^{l}-$E^{l'}$ [GeV]

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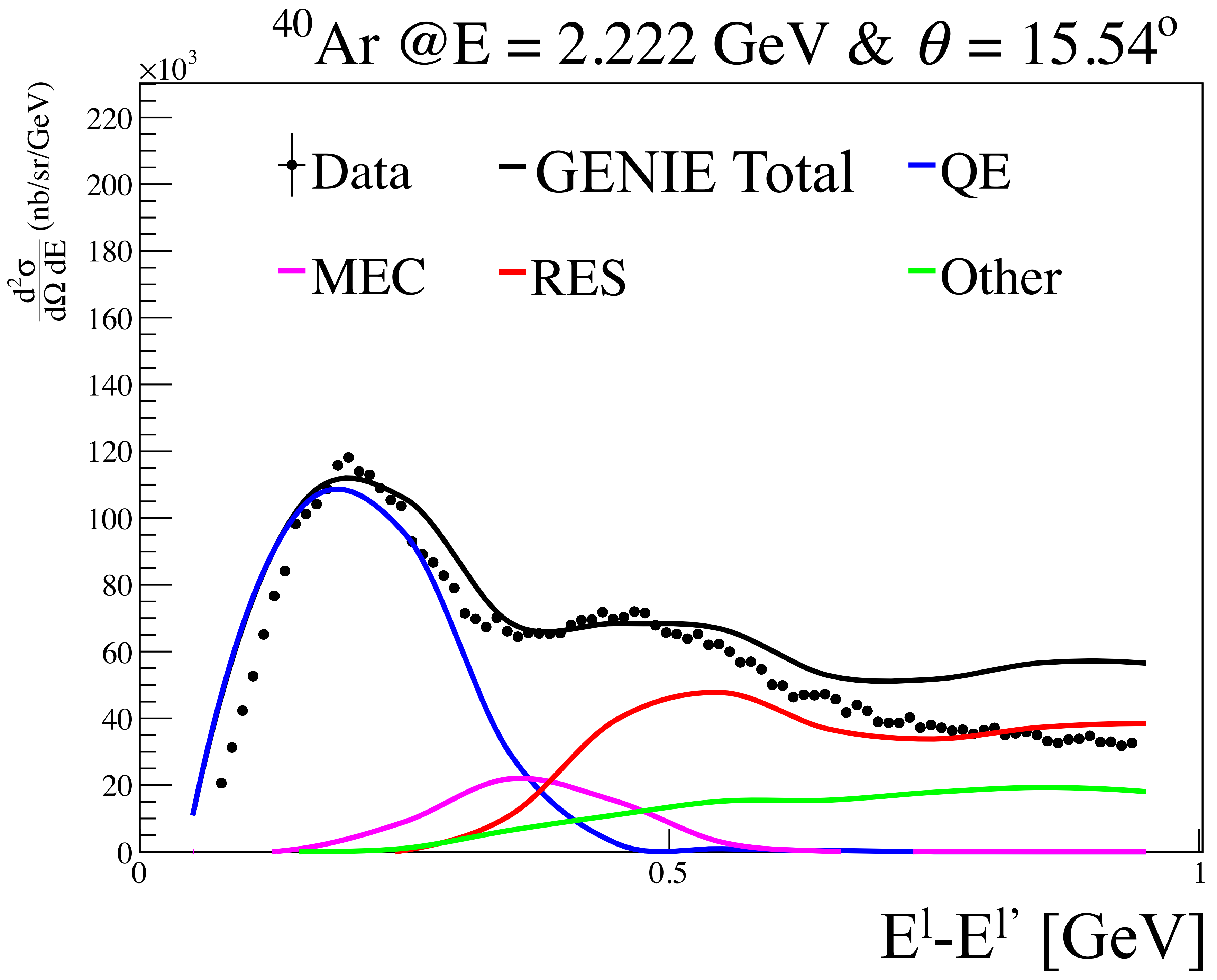
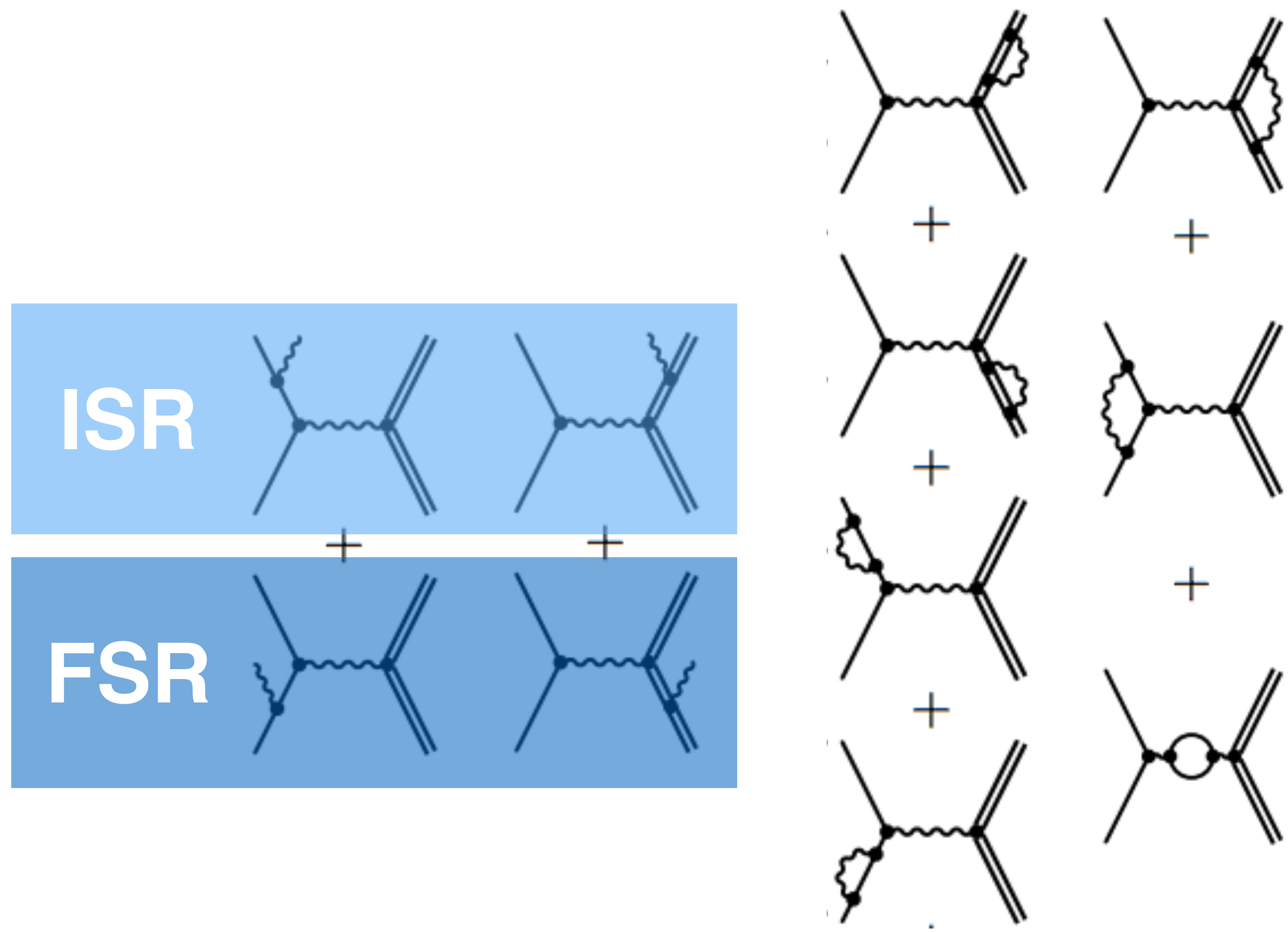


Radiative Correction

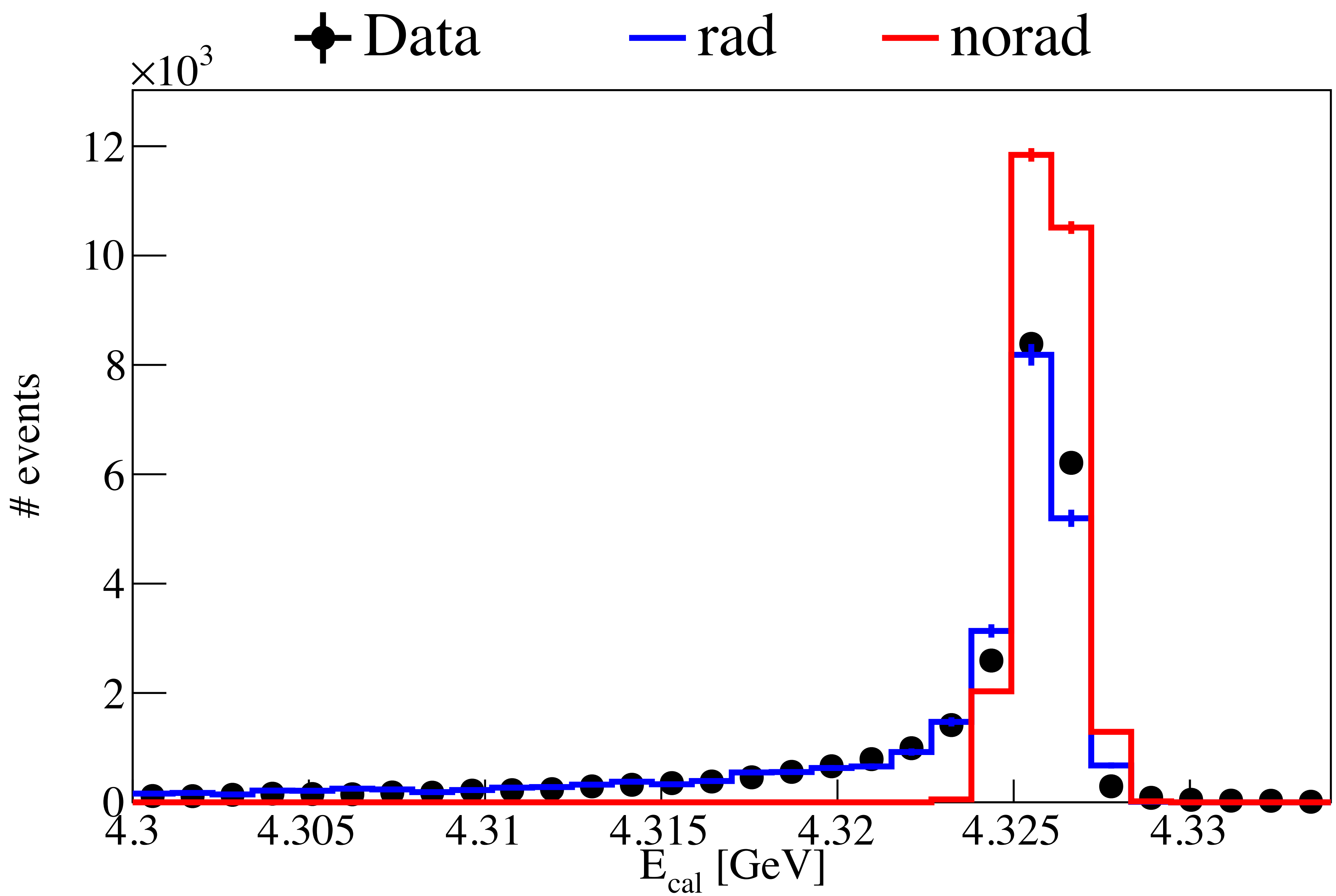
A first implementation of the radiative corrections to GENIE to account for the following processes:



Based on Mo and Tsai calculation

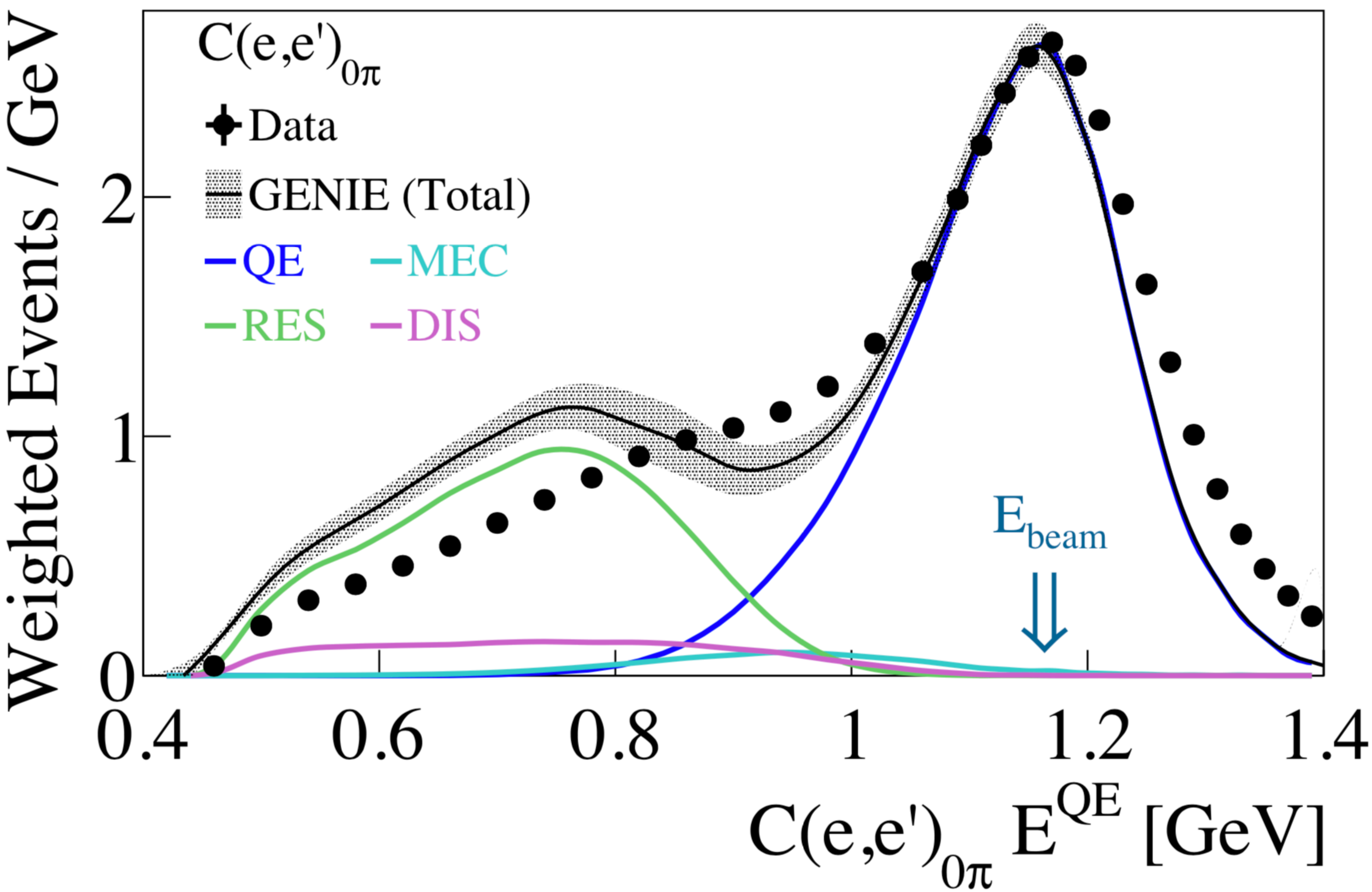
Radiative Correction - Validation

(e,e'p) @ E = 4.325 GeV on ^{1}H



Data vs. Simulation

Disagreements between Data and MC



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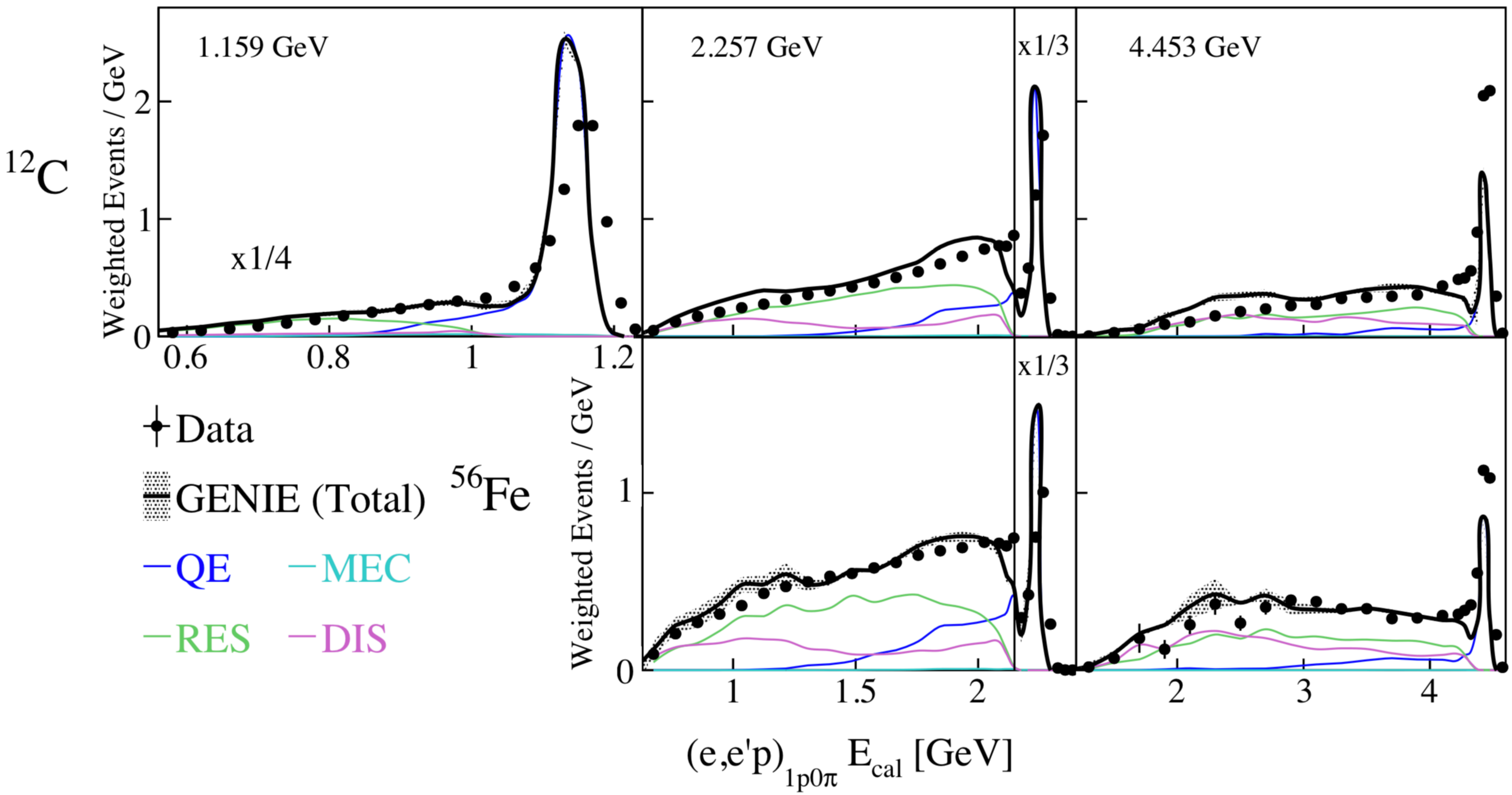
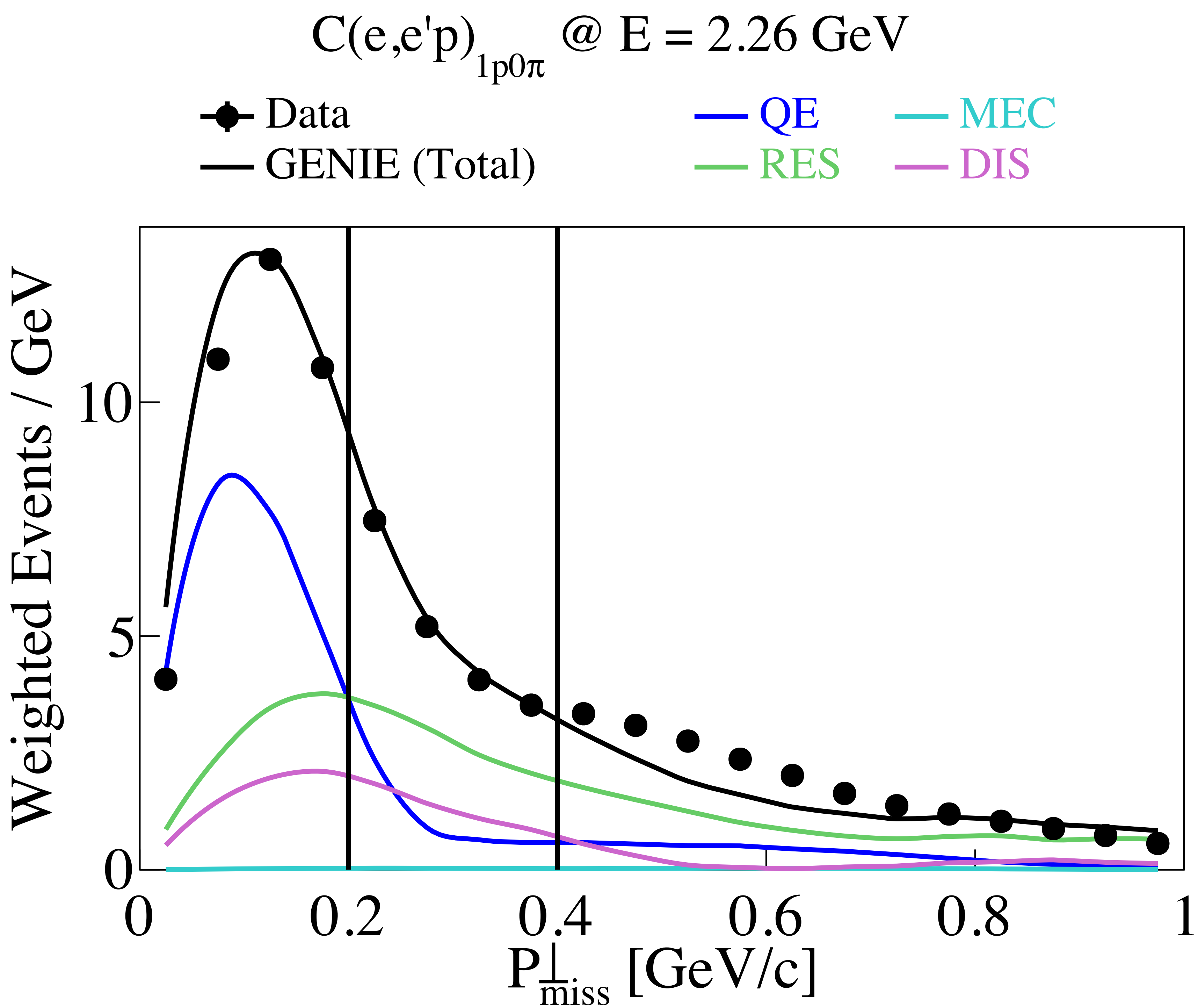


MC vs. (e,e'p) Data: $\vec{P}_{\perp}^{miss} = \vec{P}_{\perp}^{e'} + \vec{P}_{\perp}^{p}$



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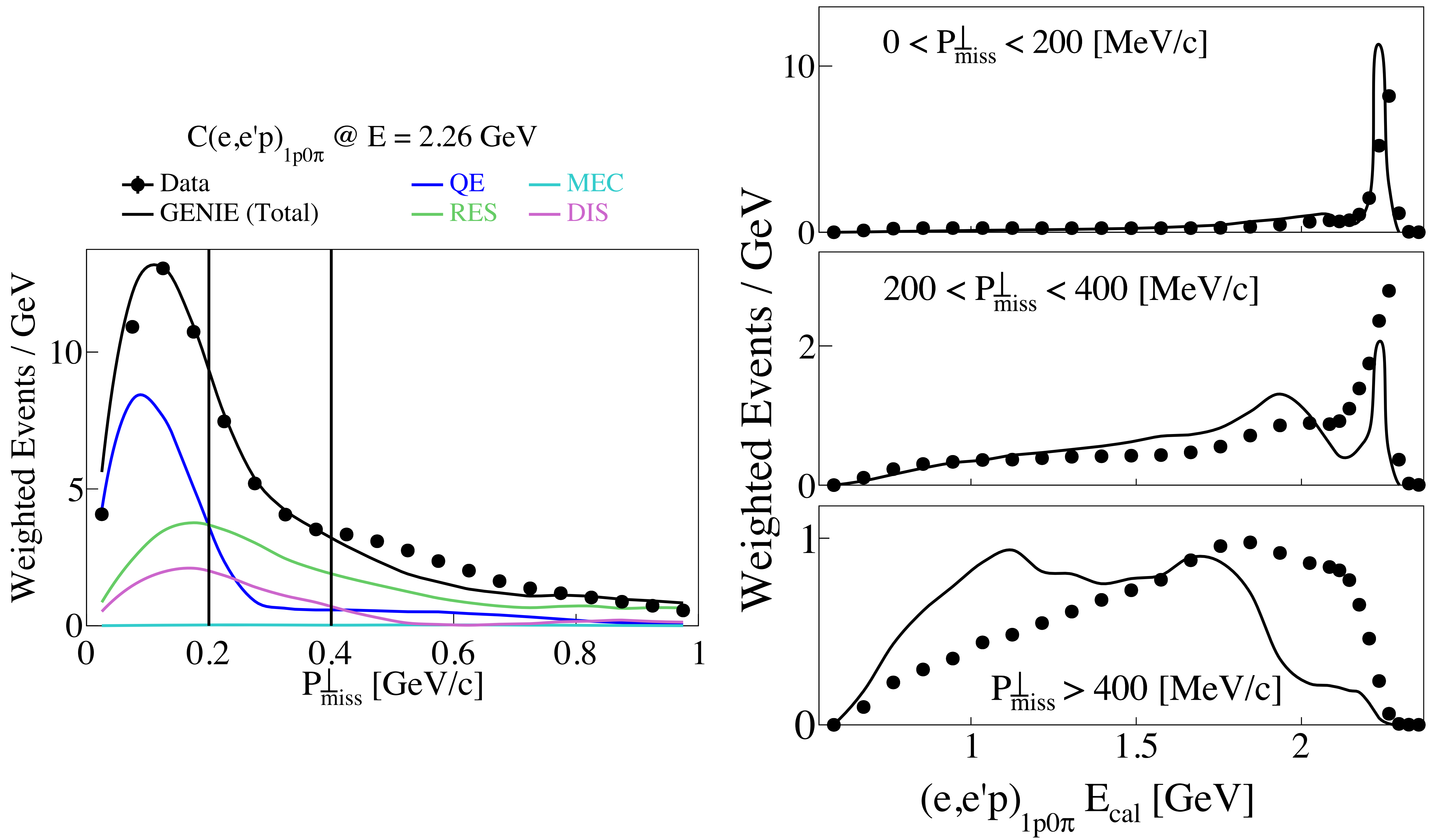
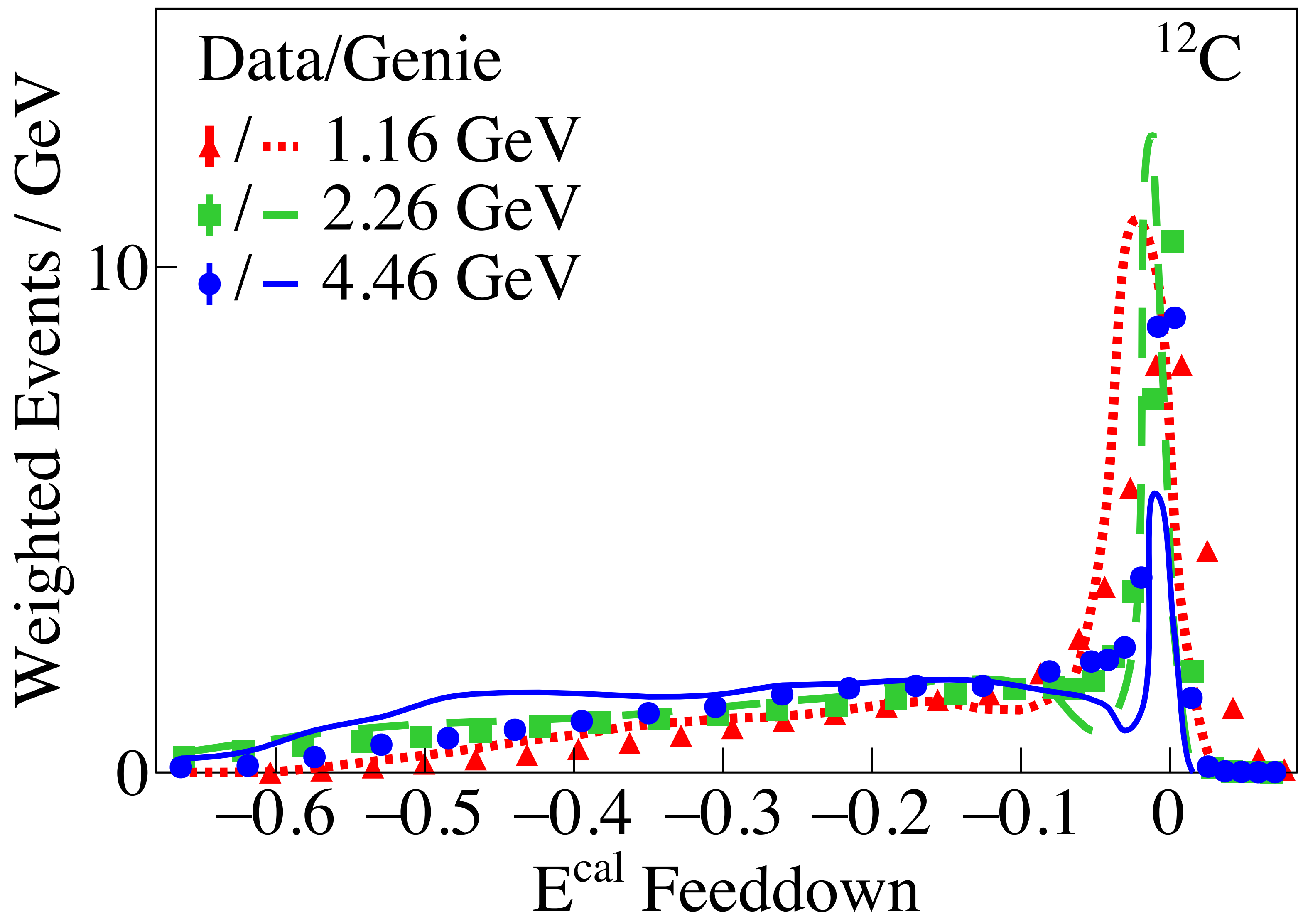


Implications and future plans

Potential implication on DUNE analysis

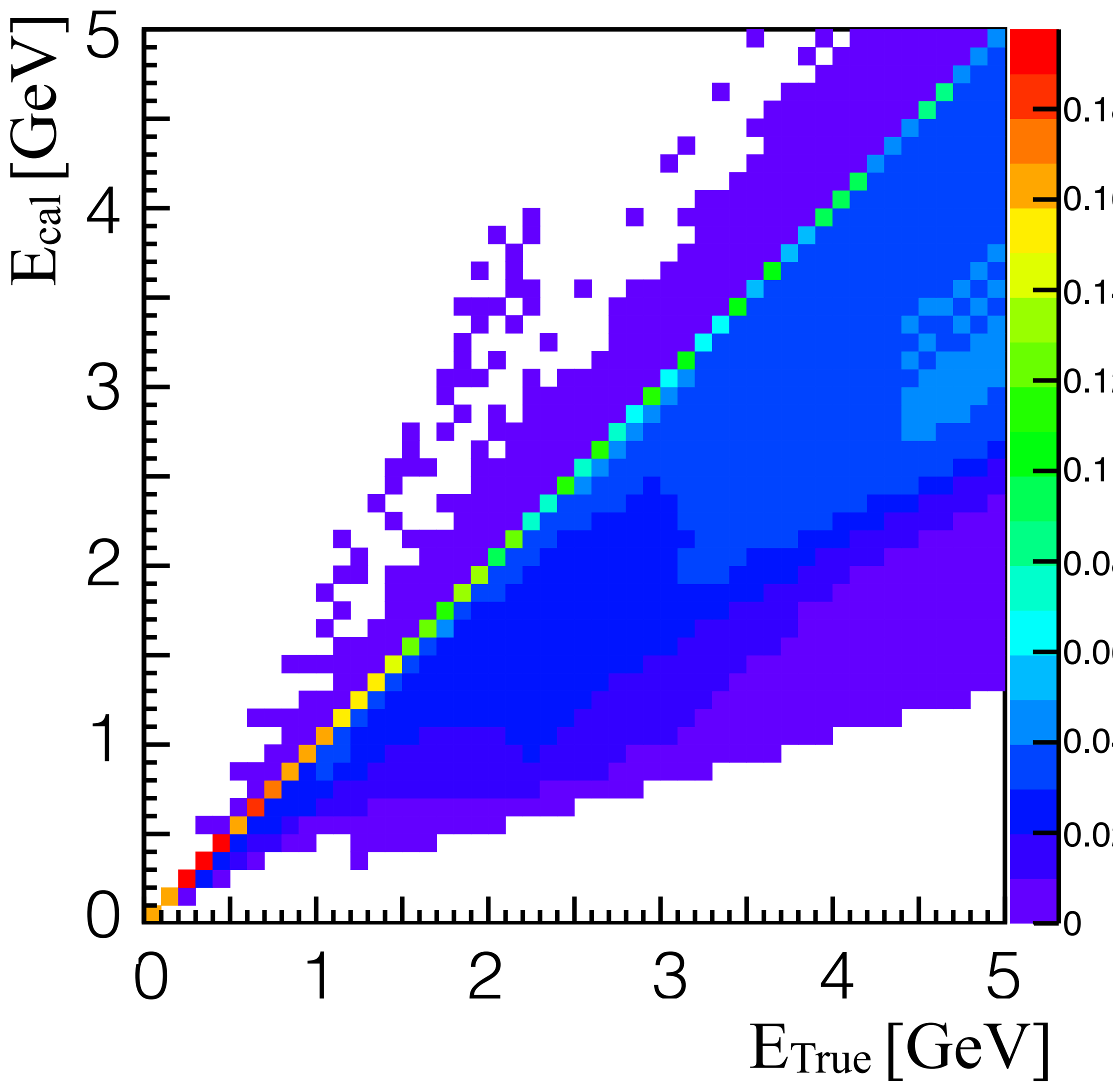
The expected energy at DUNE far detector as reconstructed using the energy feed down from A(e,e’p) data and simulation



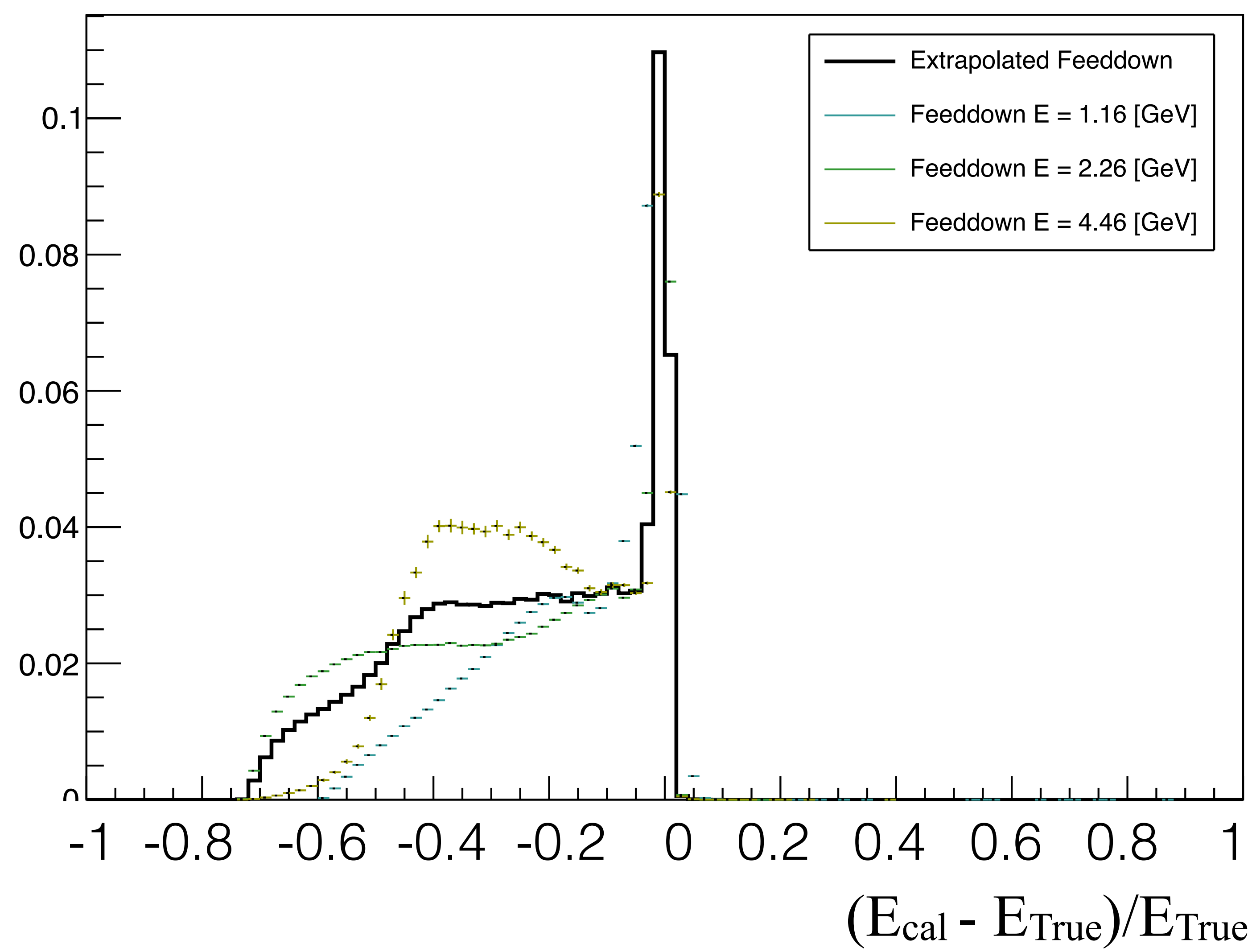
Potential implication on DUNE analysis

Extrapolating to other energies:

Extrapolated Data smearing matrix



Feeddown Ev = 3.03 [GeV]



Potential implication on DUNE analysis

The fit considers:

DUNE ν_μ to ν_e channel

Exposure of 168 kt MW yr on ^{12}C

Corresponds to 3.5 years data taking on DUNE like experiment

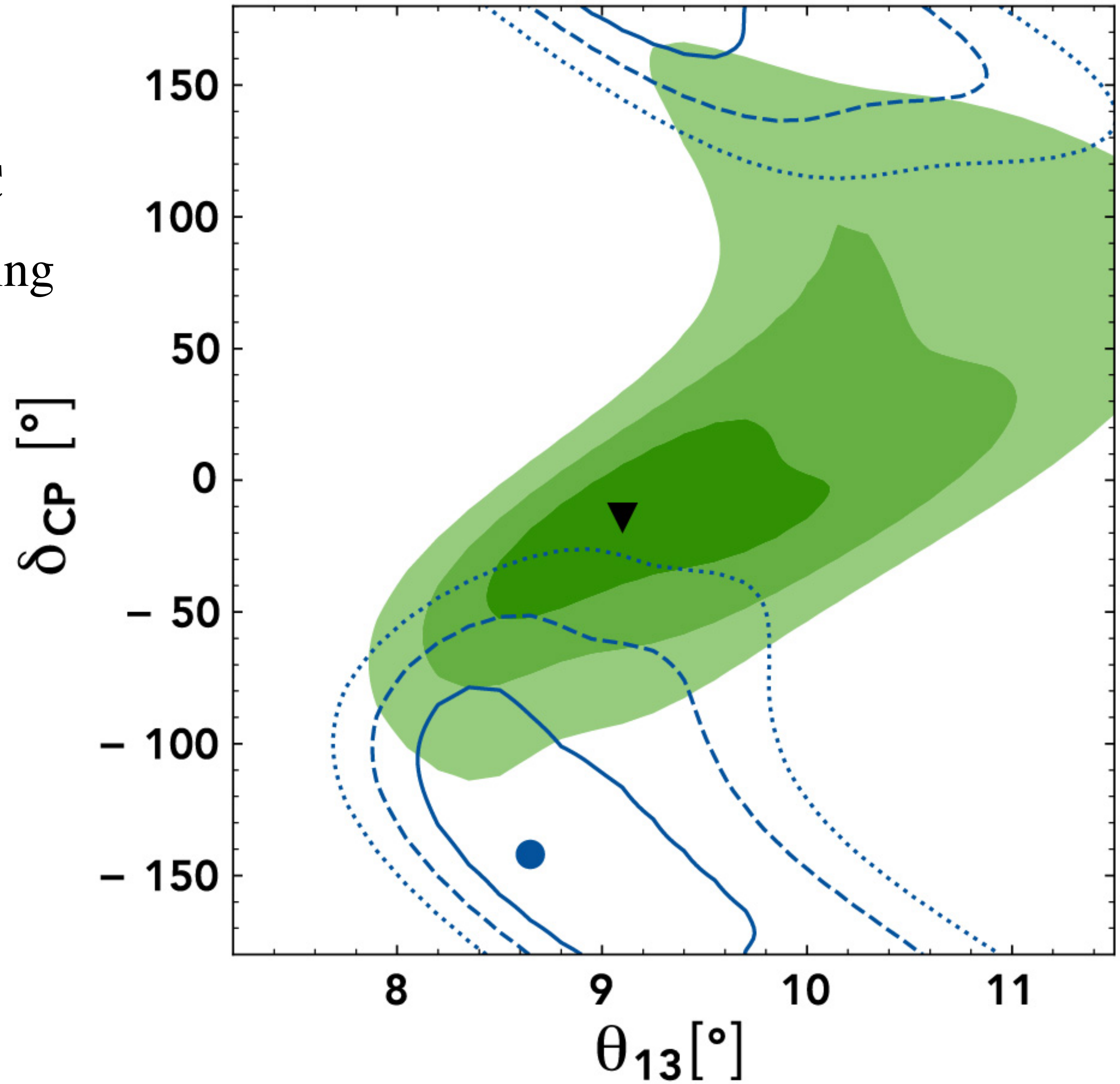
Smearing matrices based on:

1e1p selection

$\theta_e > 15^o$

$P_p > 300$ MeV/c

No $P_{\pi+/-} > 150$ MeV/c



Un-modelled nuclear effects can be mistakingly considered as oscillation effects

Future Plans -Approved run for CLAS12

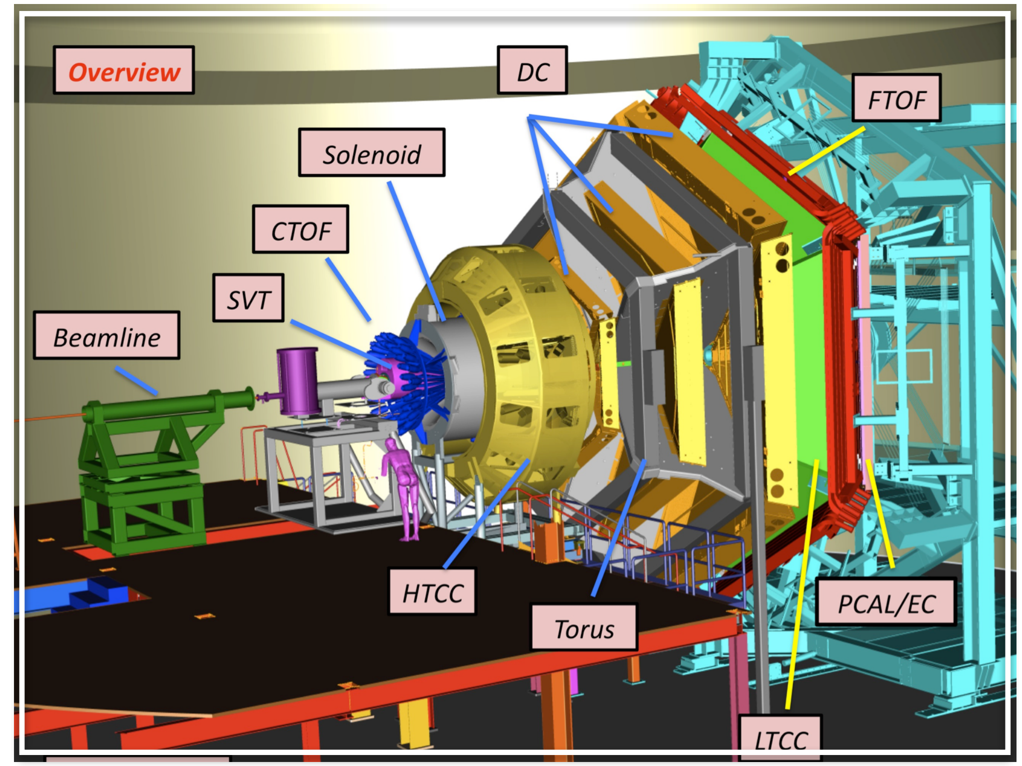
Acceptance down to 5°

x10 luminosity

Keep low thresholds

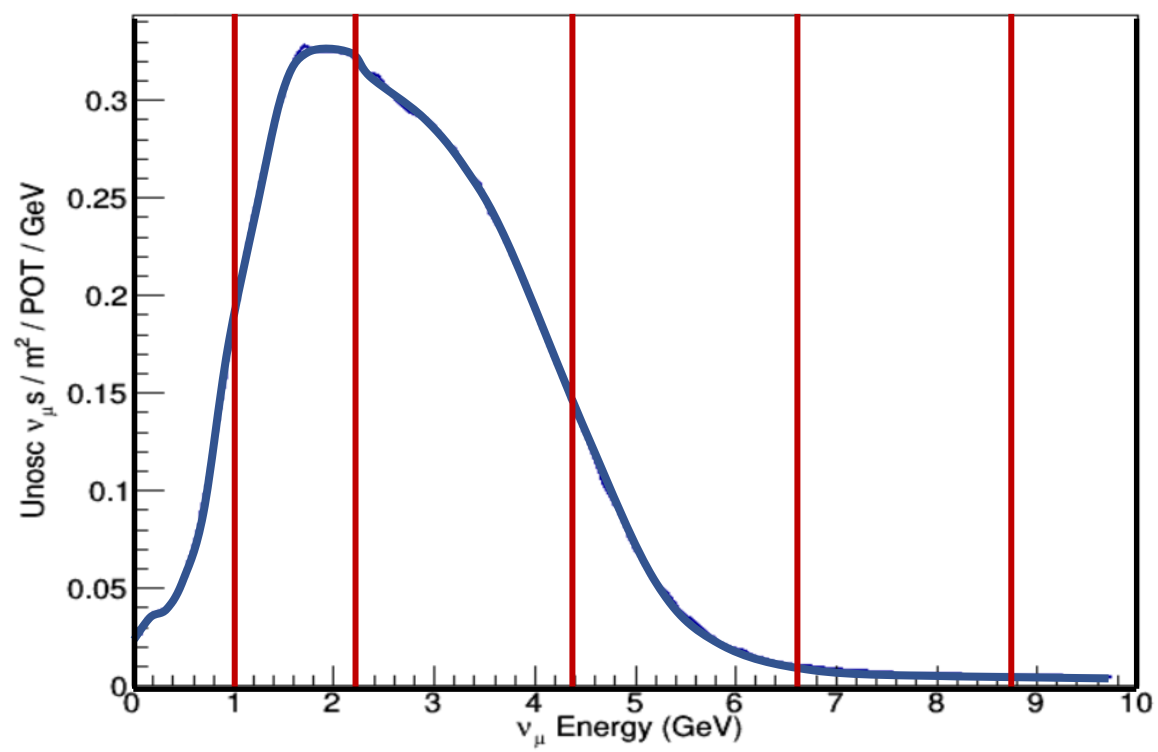
Targets: ^{2}D, ^{4}He, ^{12}C, ^{16}O, **^{40}Ar**, ^{120}Sn

1 - 7 GeV (relevant for DUNE)



Overwhelming support from:

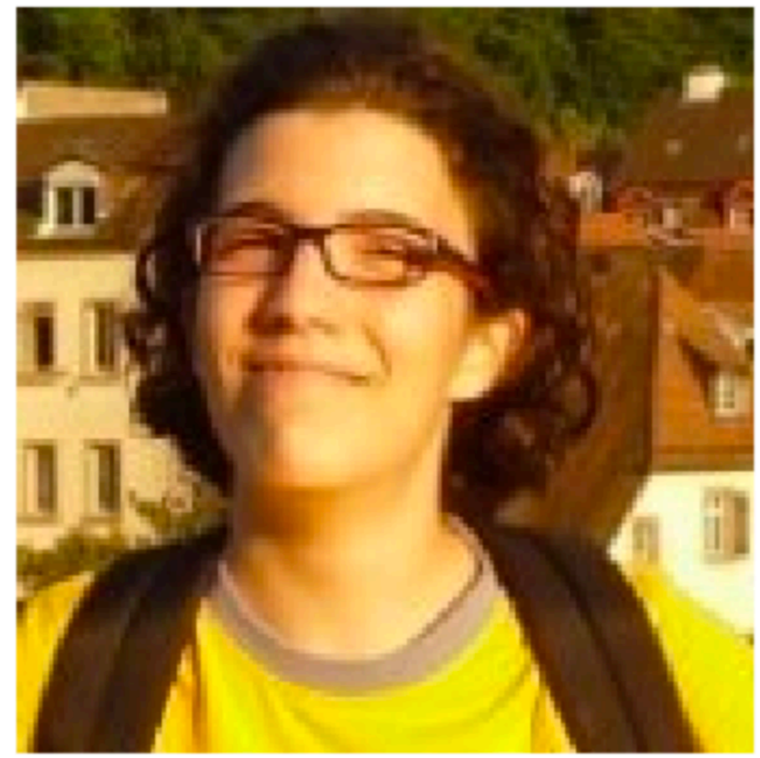
Fermilab, Hyper-Kamiokande, DUNE, MINERvA, IceCube South Pole Neutrino Observatory, NOvA, T2K, μBooNE, GiBUU The Giessen Boltzmann-Uehling-Uhlenbeck Project



e4v The team

Mariana Khachatryan

ODU @ JLab



Afroditi Papadopoulou

MIT @ FNAL

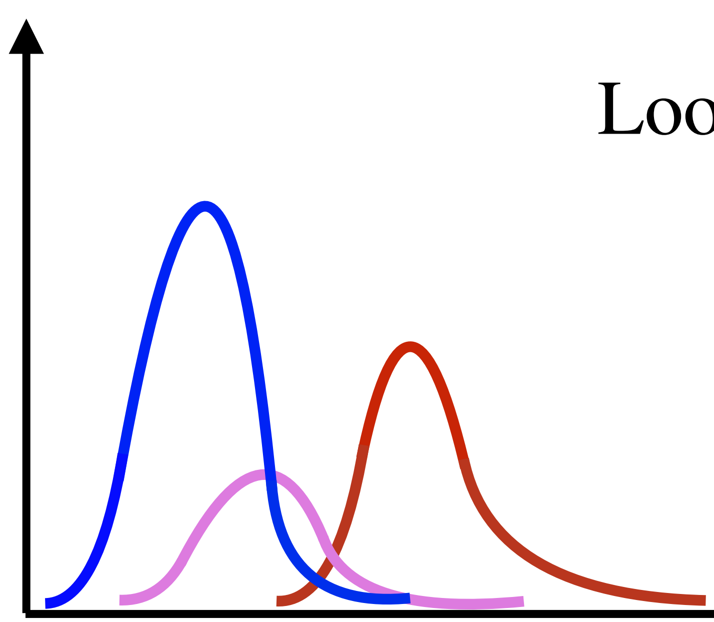
Jefferson Lab · CSIC · Consejo Superior de Investigaciones Científicas

Summary

- A wide phase space electron scattering data is used to test the methods for incoming energy reconstruction and improve νA interaction modelling.
- Disagreement between data and event generators, with significant implications on DUNE analyses.
- For QE-like events both leptonic and hadronic reconstructed energies have bad resolution, Especially for heavier nuclei, high missing transverse momentum.

Looking forward to expand the phase space and obtain new data with more relevant nuclei, energies and processes

starting with resonances most relevant to DUNE



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Thank you for your attention